# DESIGNING TURBINE ENDWALLS FOR DEPOSITION RESISTANCE WITH 1400C COMBUSTOR EXIT TEMPERATURES AND SYNGAS WATER VAPOR LEVELS

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"THE" BRIGHAM YOUNG UNIVERSITY

(3-year grant awarded Oct 2008 – 6 Month Extension)

# MOTIVATION/NEED

- Operational Issues
  - -Fuel flexibility (range of feedstock heat release)
  - -Diluent use (e.g. steam)
  - -Filtration requirements

- Technical Challenges
  - - Higher firing temperature
  - - Increased heat transfer (steam diluent)
  - - Potential for increased levels of airborne contaminants
  - - Deposition rate increases with temperature
  - - Advanced cooling, greater reliance

# OBJECTIVES

The objectives of this work are to study turbine deposition at elevated gas temperatures and water vapor levels
AND
explore modifications to turbine endwall geometries that reduce the potential for degradation due to deposition.

The effort includes both experimental and computational components, with work divided into three phases.

1) Modeling and Experimental Validation
2) CFD and Experimental Endwall Design Study
3) CFD Design Study with Cooling & Experiments with Steam

# RESEARCH TEAM

**TEAM LEAD**
Focus: Experimental Heat Transfer and Deposition Measurements in OSU Turbine Reacting Flow Rig

**Dr. Jeffrey Bons**
Professor
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Columbus, OH

**Co-PI**
Focus: Deposition Model Development and Heat Transfer CFD

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Research Scientist
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**Co-PI**
Focus: Experimental Work in BYU's Turbine Accelerated Deposition Facility with Elevated Temperatures (1400C) and Steam Injection

**Dr. Thomas Fletcher**
Professor
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Brigham Young University
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# RESEARCH FOCUS

Gas Turbine Deposition Accelerated by
Steam Diluent Injection used for NOx Control

Research at **OSU** will explore turbine flow passage and/or cooling designs that either:
i) have performance less sensitive to surface degradation due to deposition, erosion, and corrosion, or
ii) alleviate flow path deposition, erosion, and corrosion.

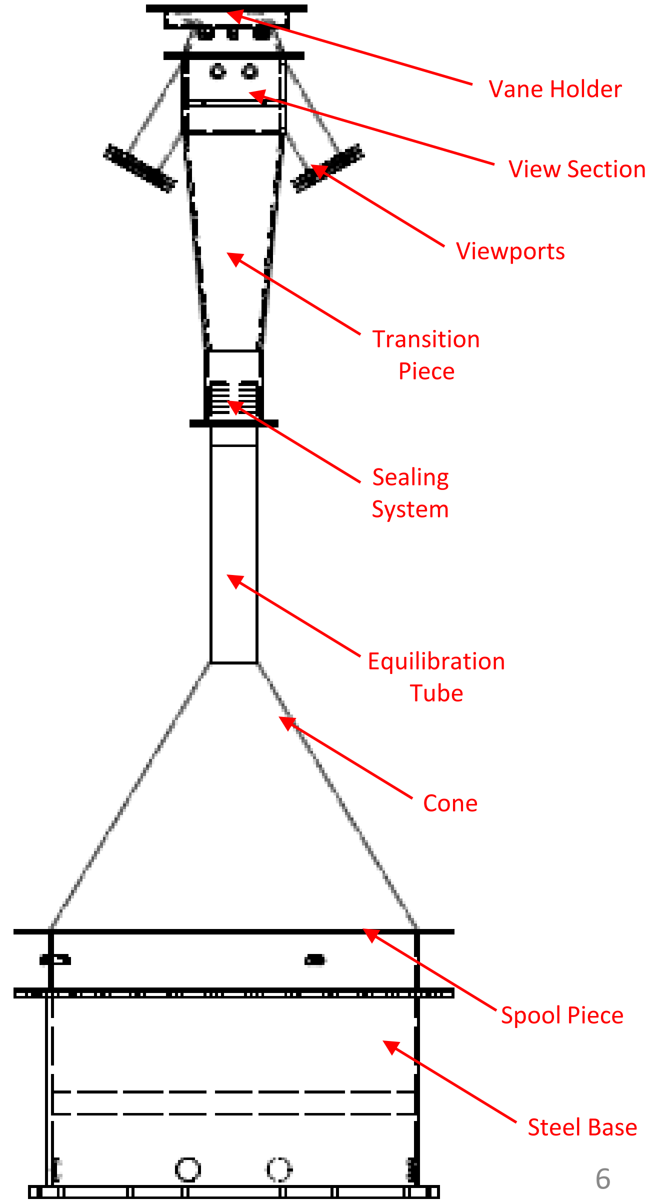
Deposition models developed at **OSU** will be validated with experimental data from **OSU** and **BYU** deposition facilities and incorporated into commercially available CFD.

Research at **BYU** will explore the sensitivity of deposition to:
i) Gas temperatures over the range 900-1400C
ii) Water vapor concentrations up to 25%

Failed turbine rotor platform
with elevated deposition

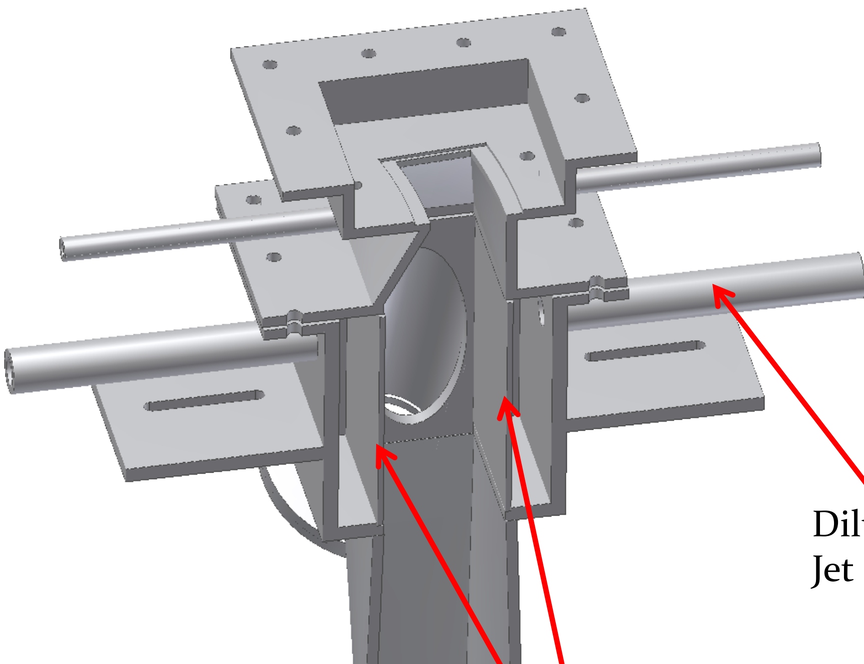
# OSU's Turbine Reacting Flow Rig (TuRFR)

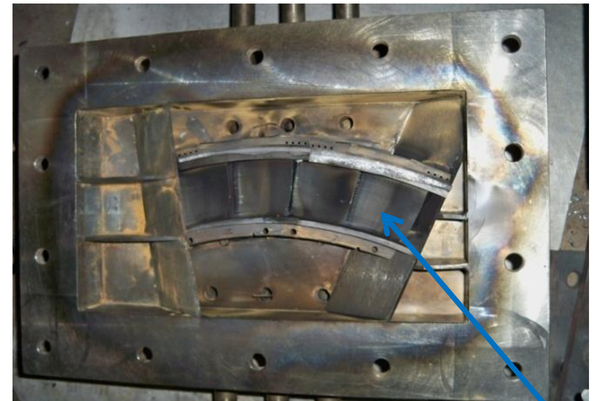
- Natural gas burning combustor rig
- Combustor exit flow accelerated in cone nozzle
- Transition from circular to annular sector
- Real vane hardware (CFM56) installed in annular cascade sector
- Tt4 up to 1120°C (2050°F)
- Inlet Mach number ~ 0.1
- $300{,}000 < Re_{cex} < 1{,}000{,}000$
- Adjustable inlet temperature profiles
- Adjustable inlet turbulence profiles (through dilution jets)
- Film cooling from vane casing and hub (density ratio 1.6-2.0)
- Ash particulate feed in combustion chamber (10 μm MMD)

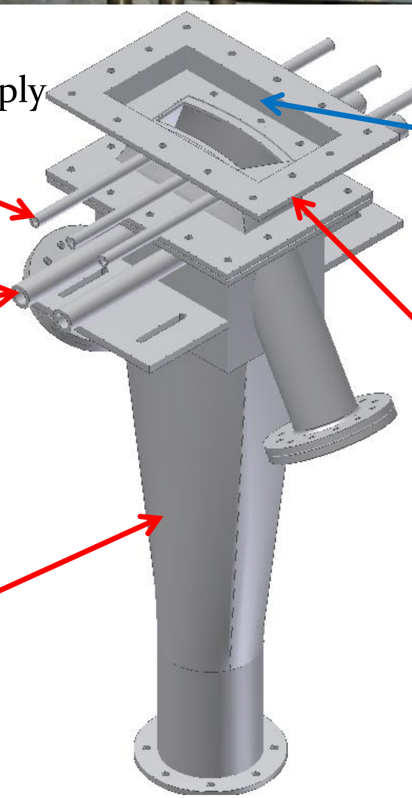


# OSU's Turbine Reacting Flow Facility (TuRFR)

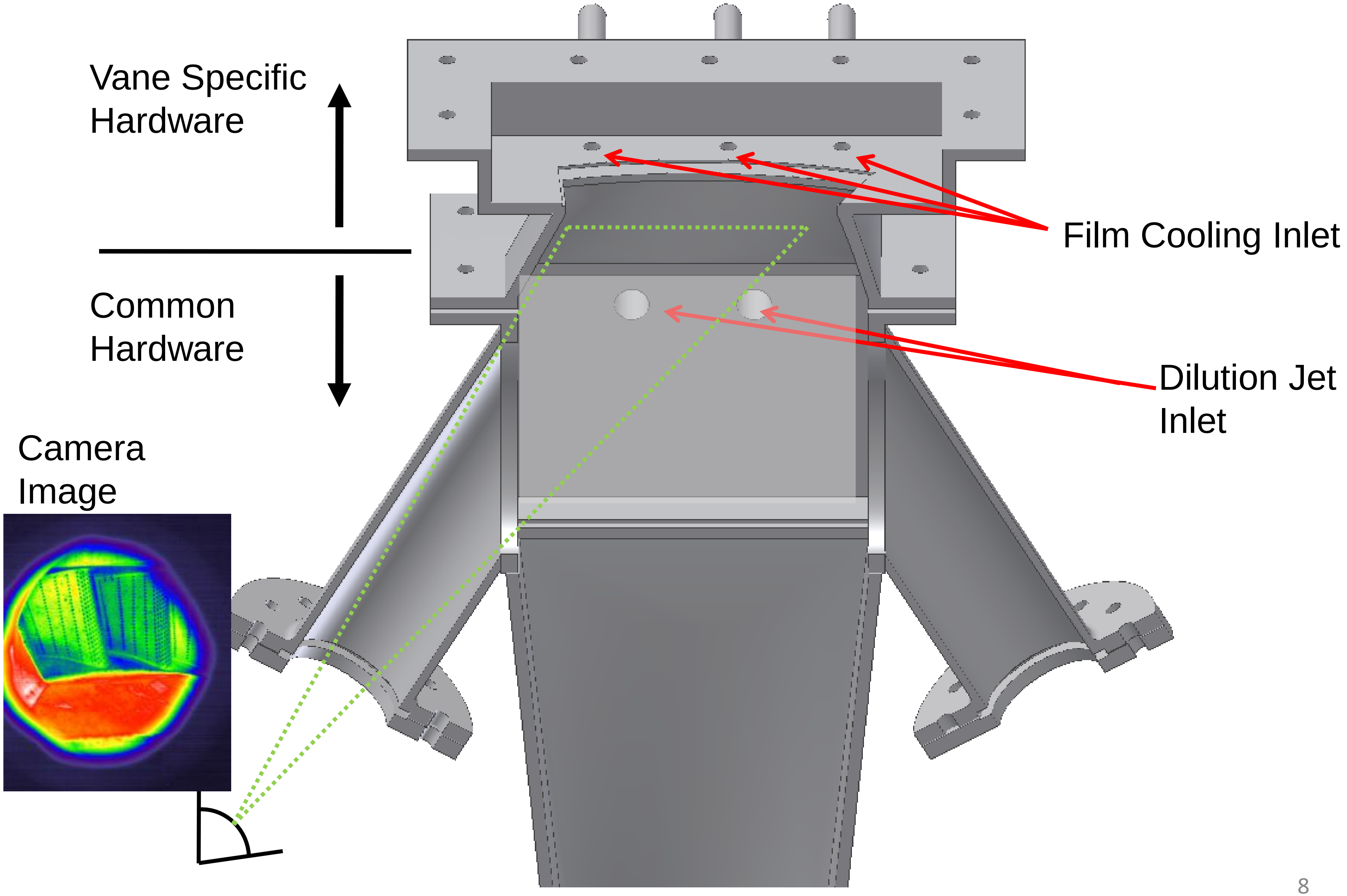
Vane Holder and Upstream Conditioning



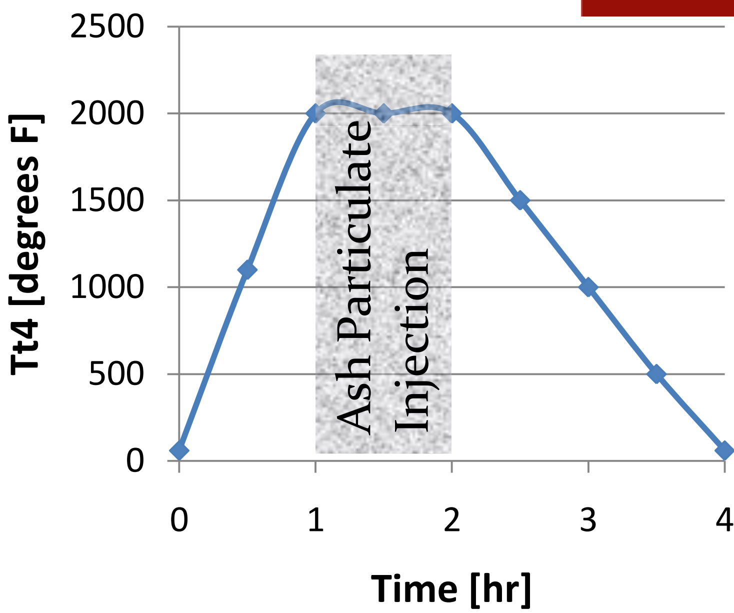


# OSU - TuRFR


Vane Specific
Hardware
Common
Hardware
Film Cooling Inlet
Dilution Jet
Inlet
Camera
Image

# Typical TuRFR Test Profile

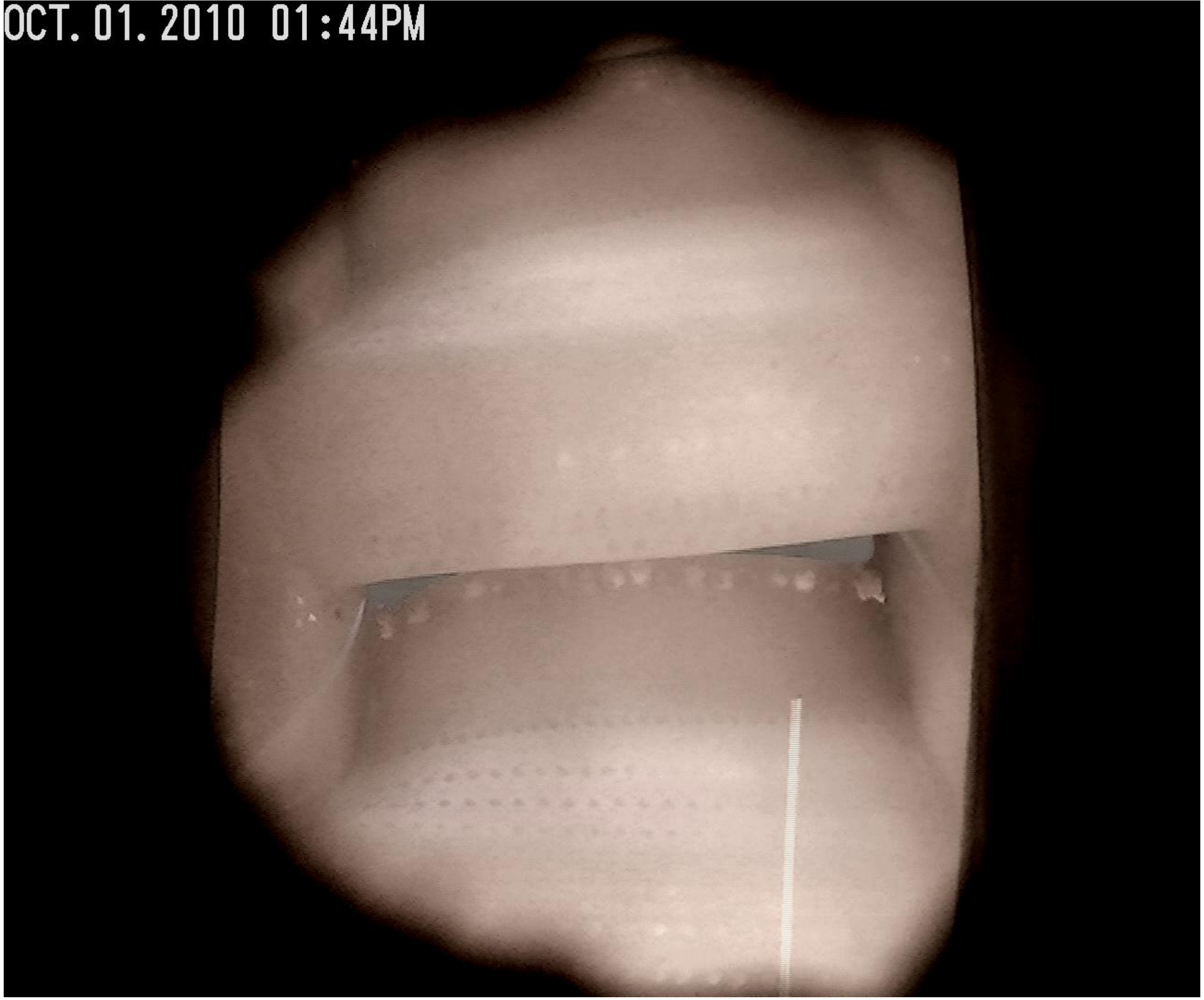
Before



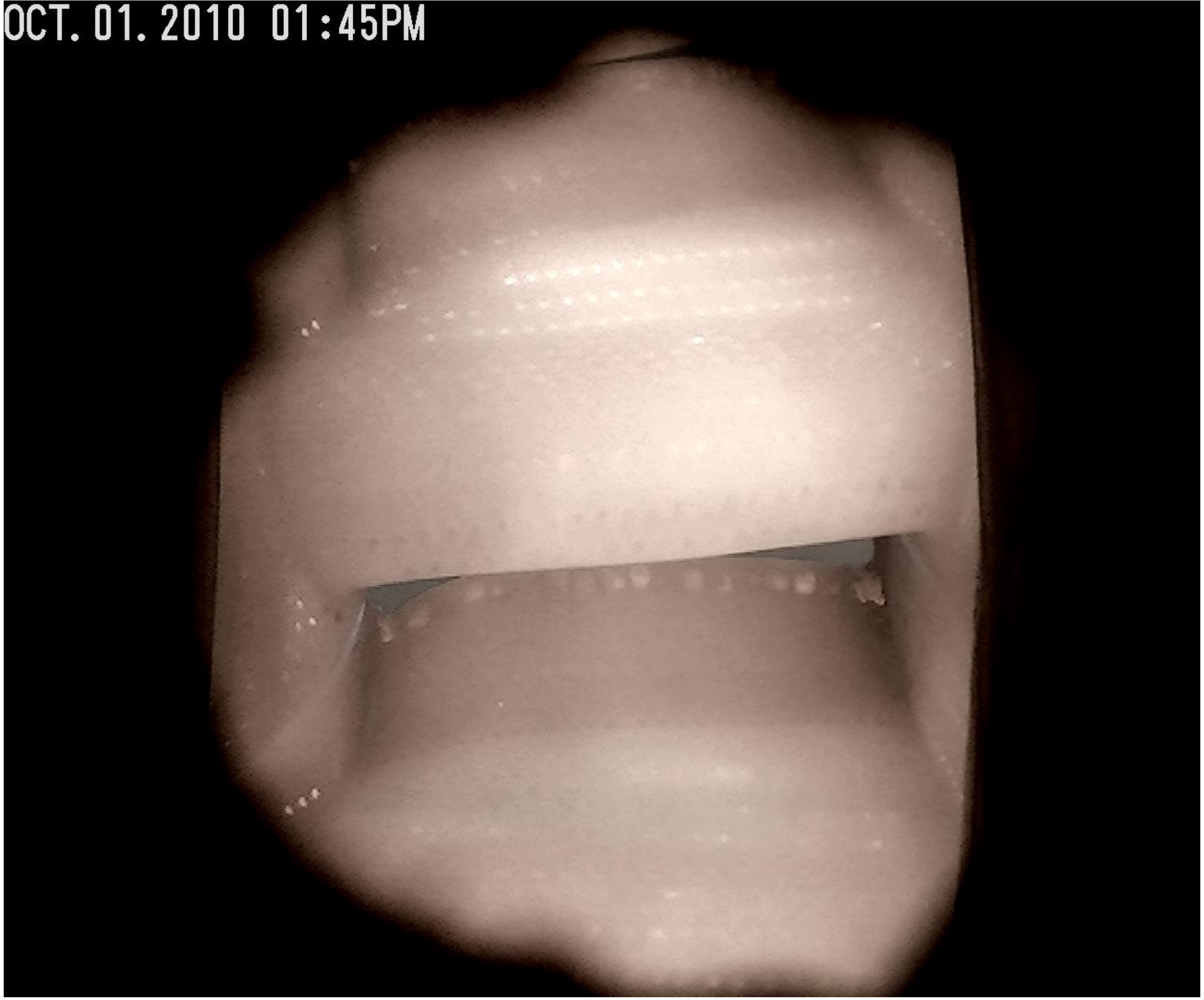

After

# TuRFR Results

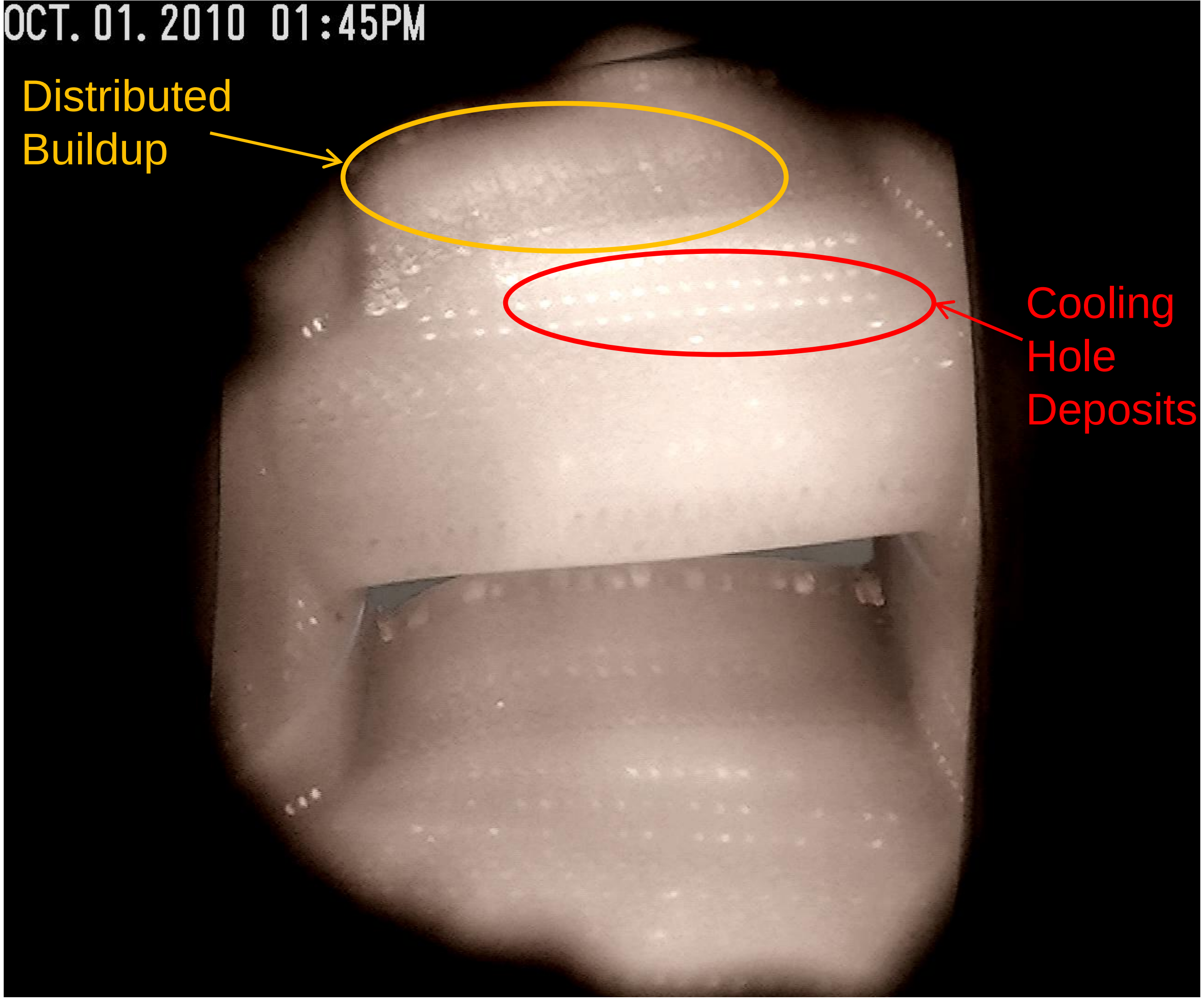
Typical Test Run



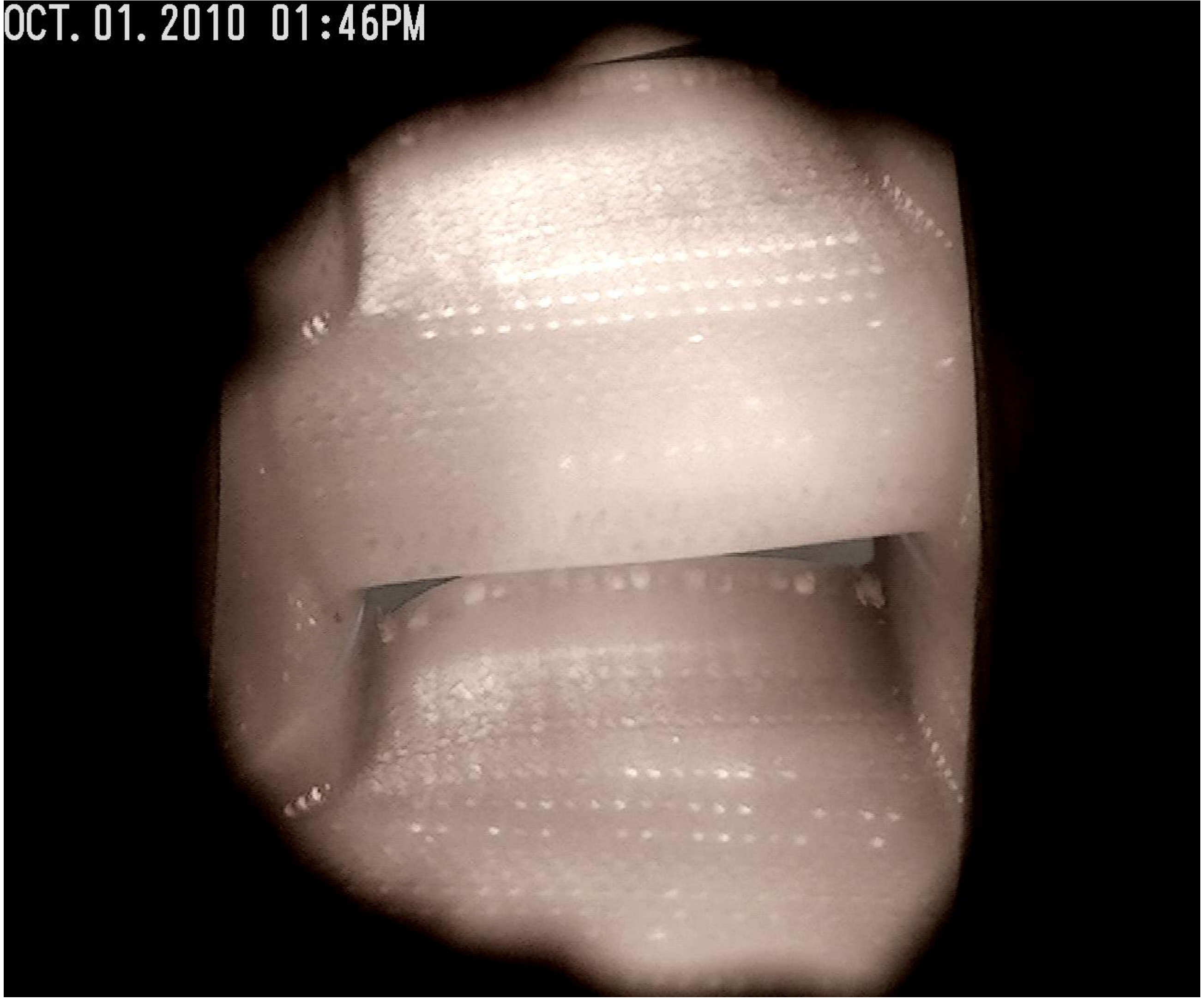

Test on 10/1/10
Wyoming (Jim Bridger Power Station)
Sub-Bituminous Ash (from BYU)
Test Conditions: ~1900 F; M=0.09; No Cooling
t=0 sec



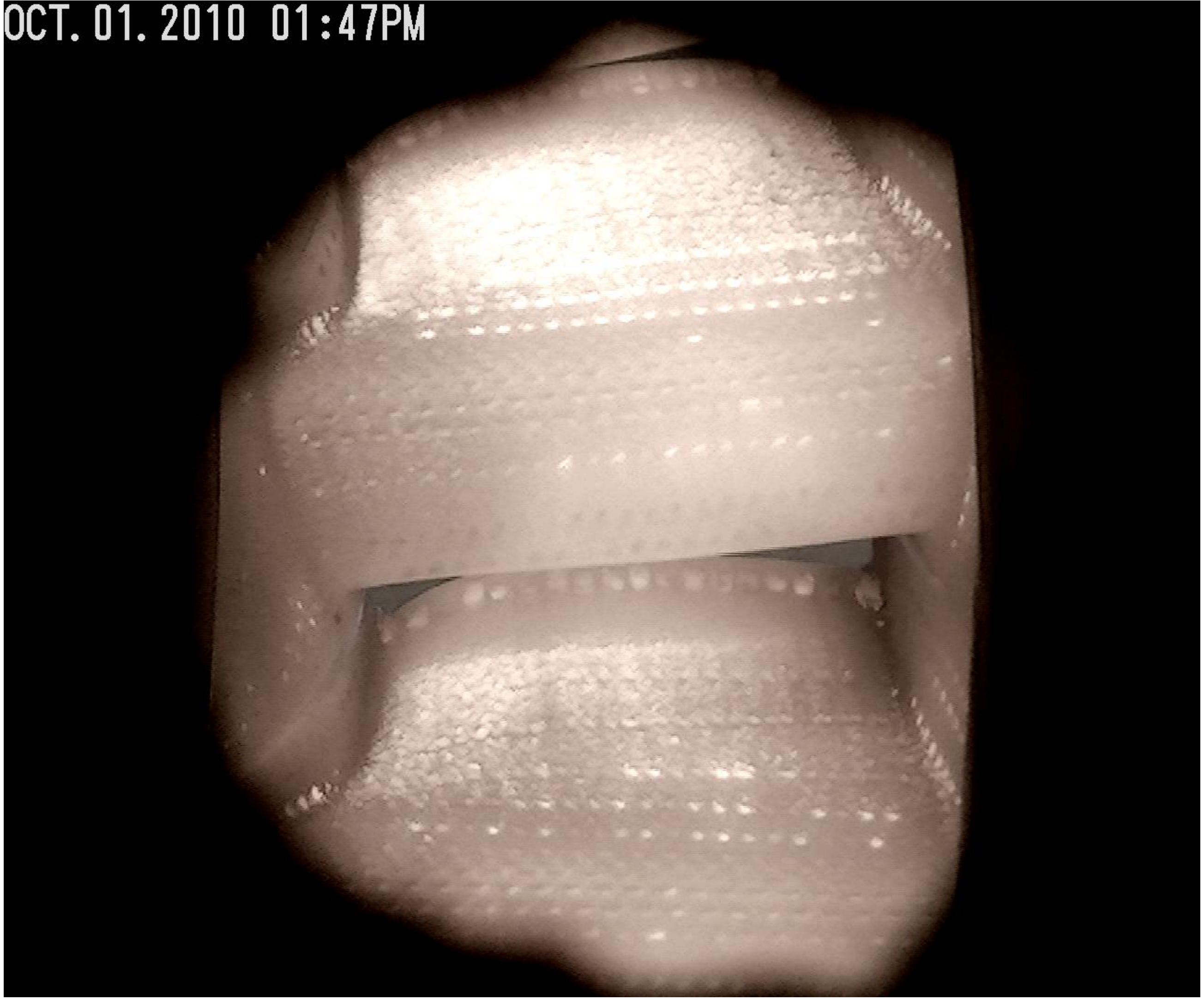

t= +30 sec


OCT. 01. 2010 01:45PM
Distributed
Buildup
Cooling
Hole
Deposits

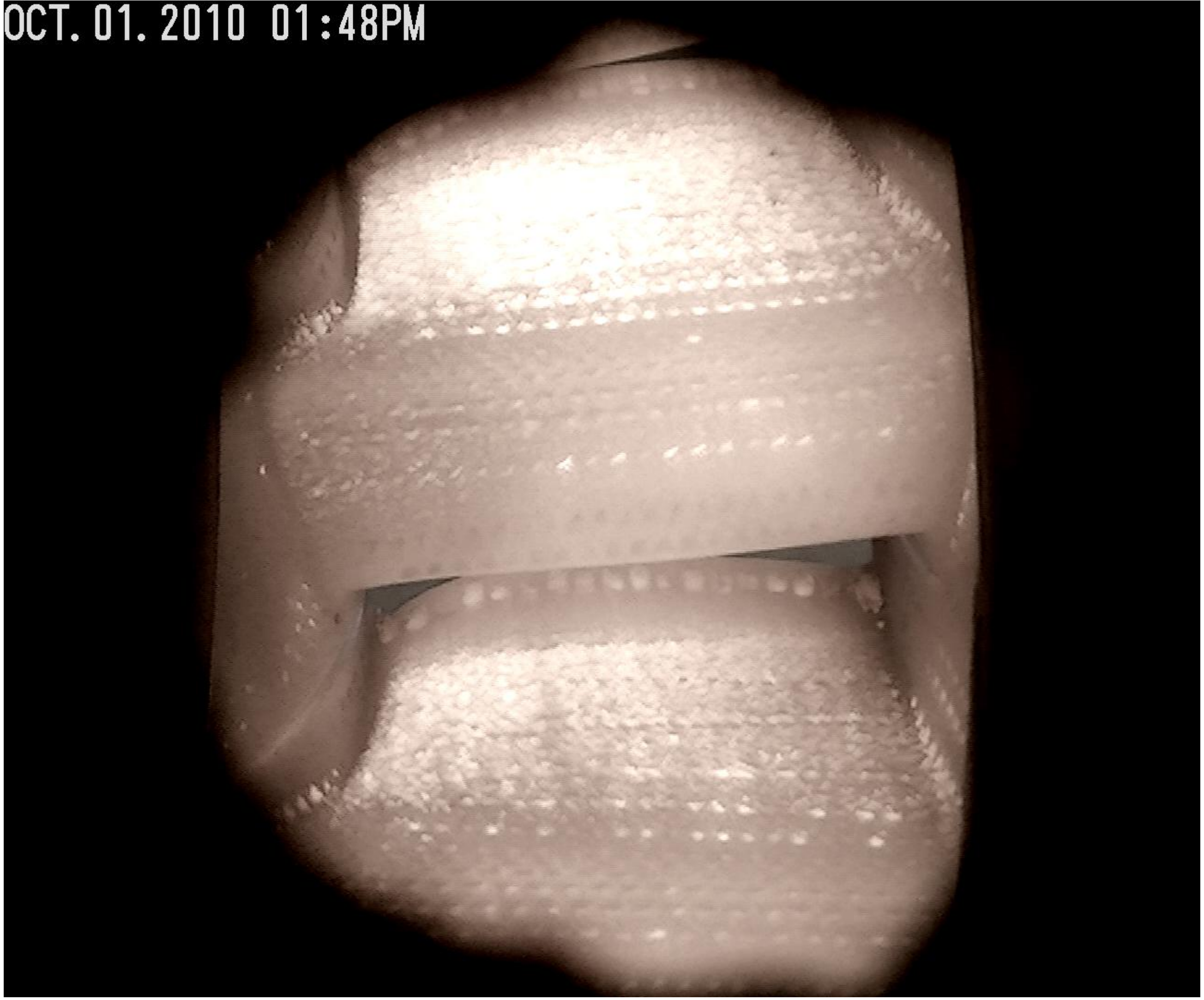
t= +1 min



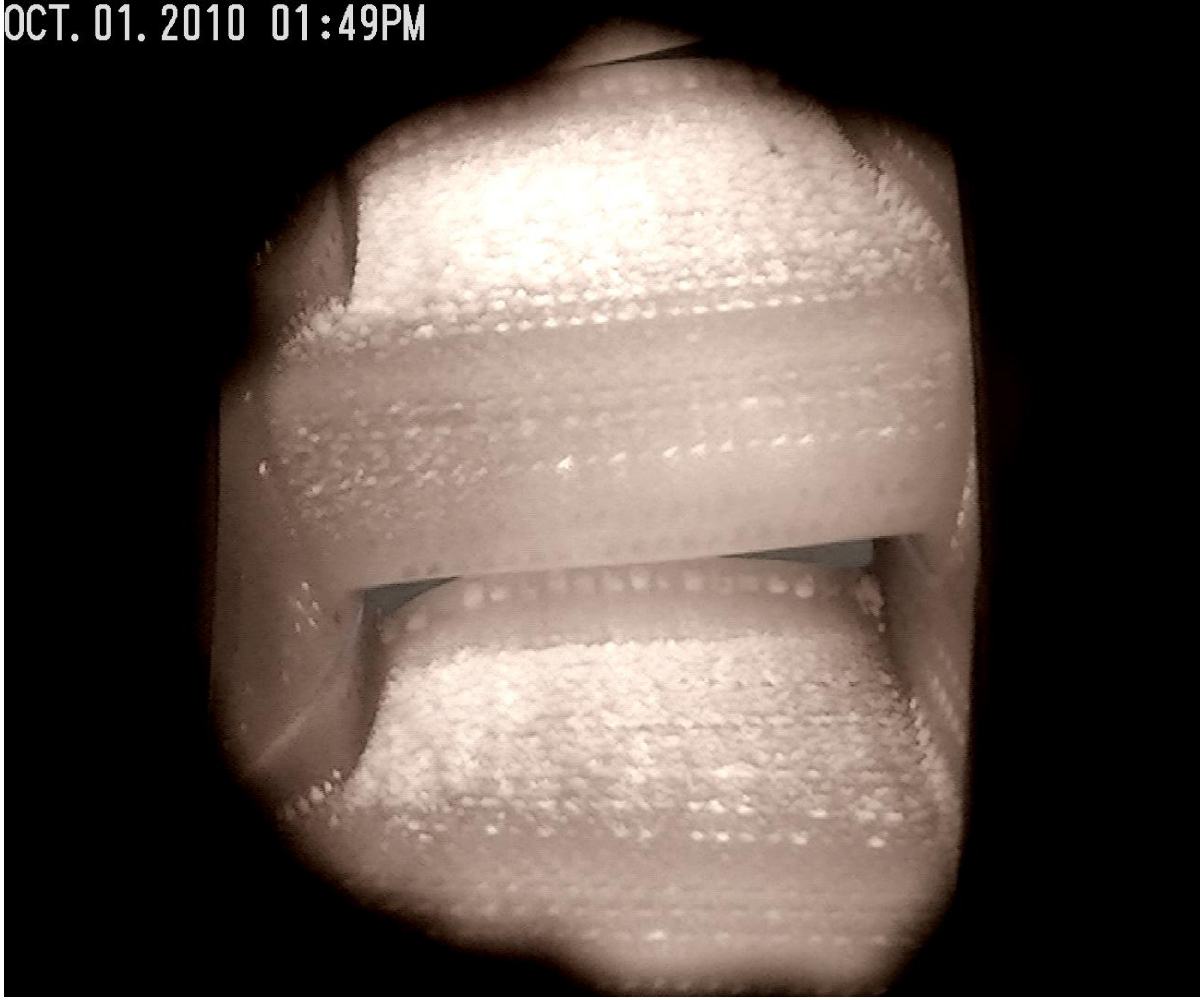

t= +2 min



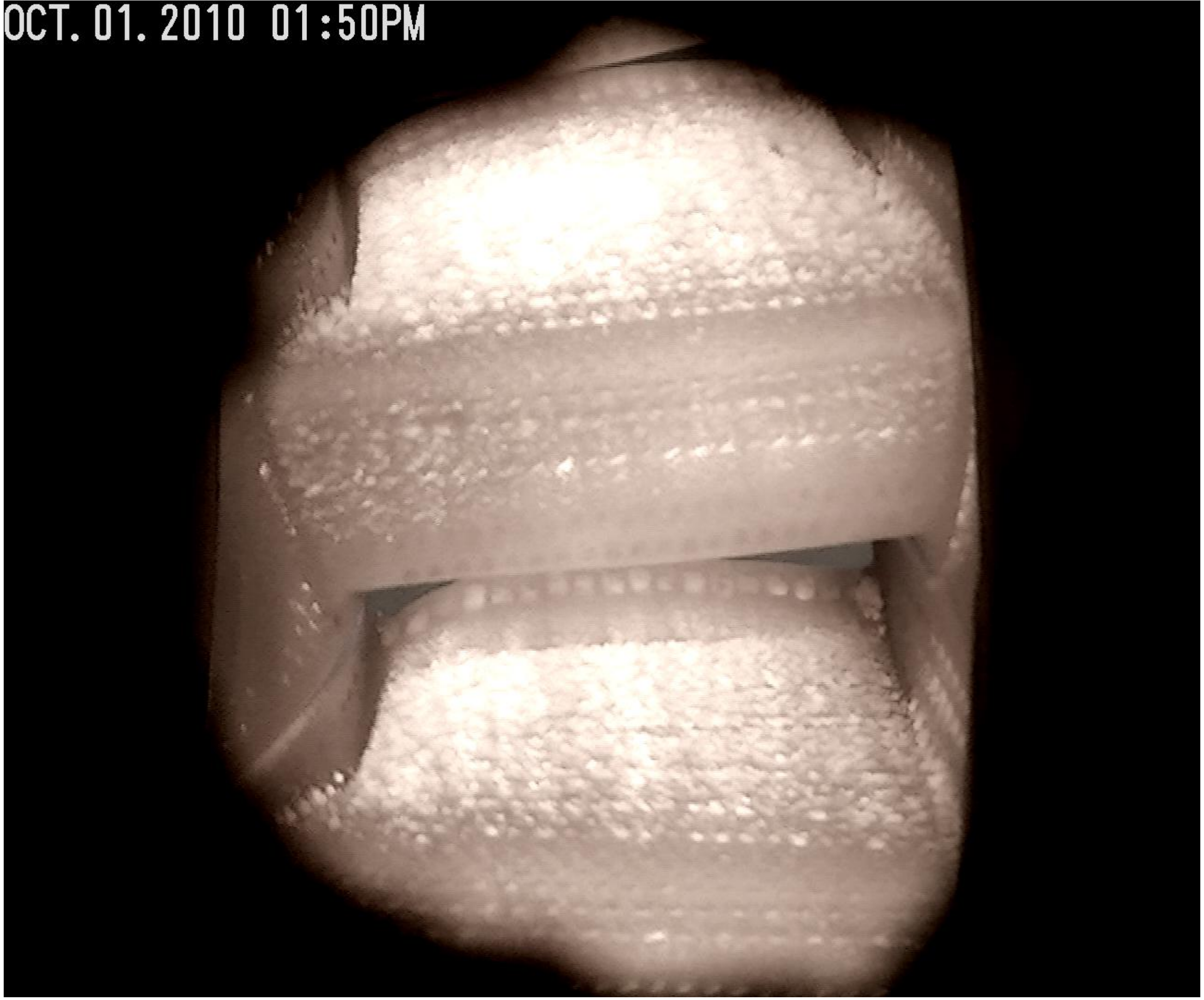

t= +3 min



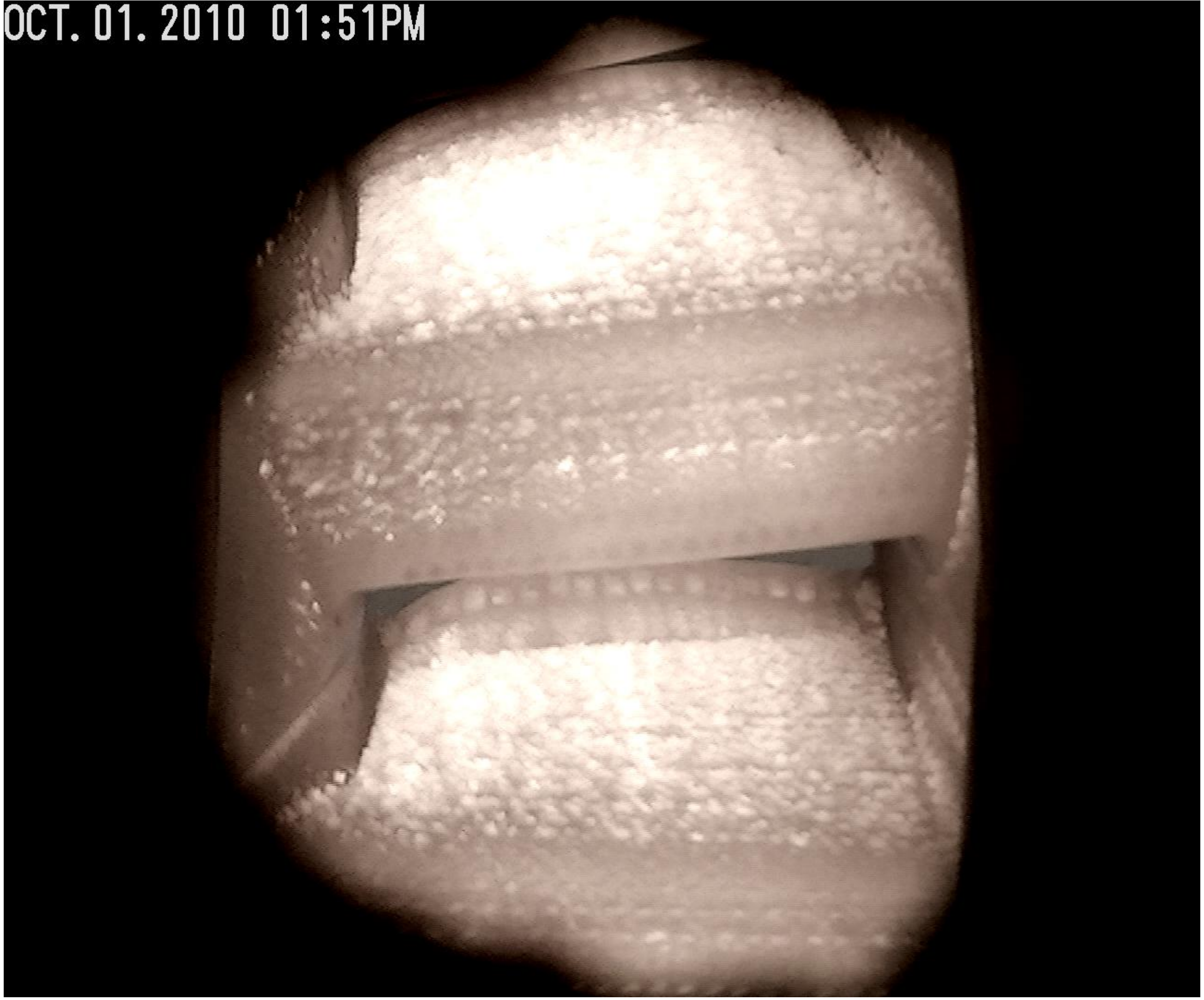

t=+4 min



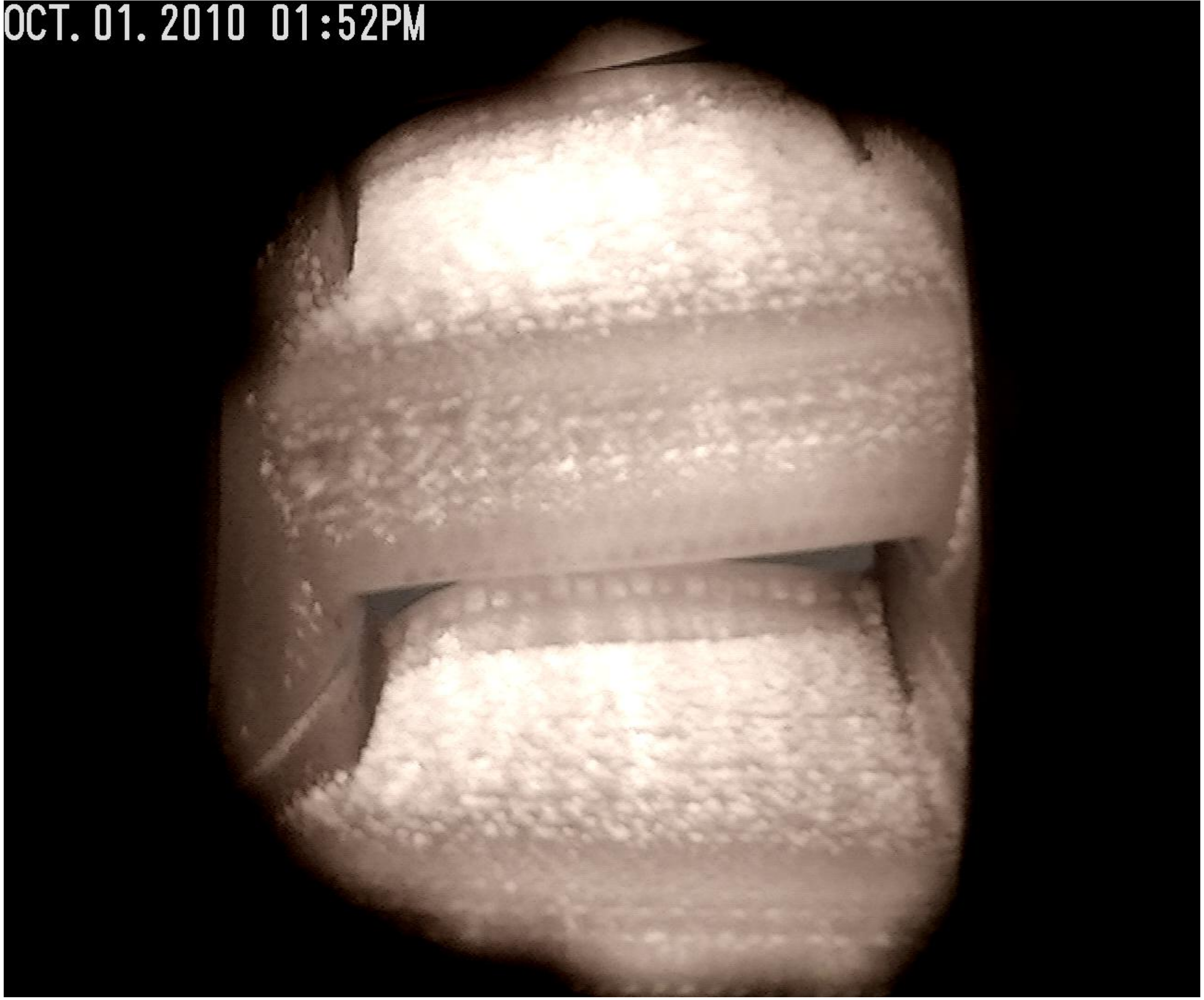

t= +5 min



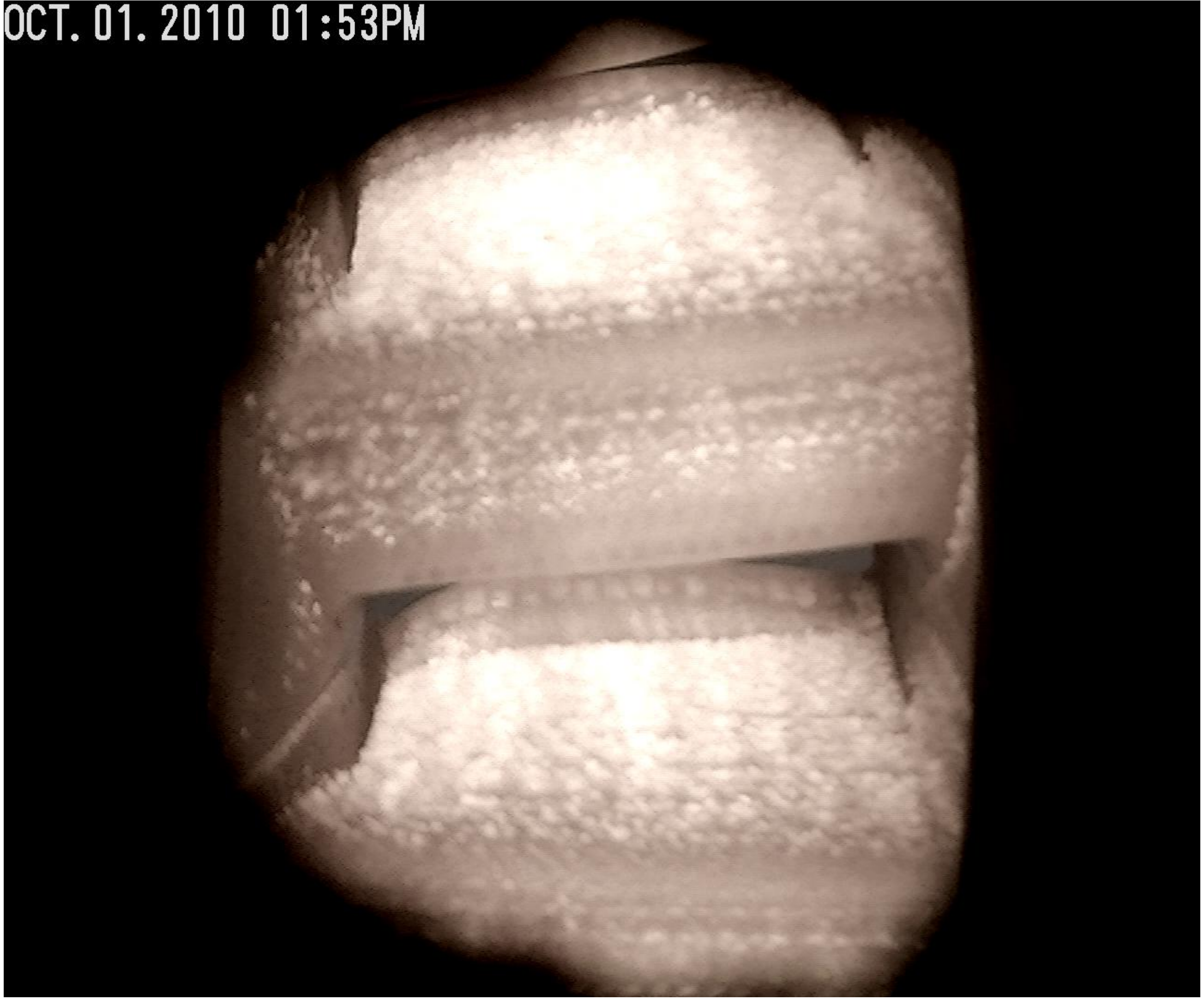

t=+6 min



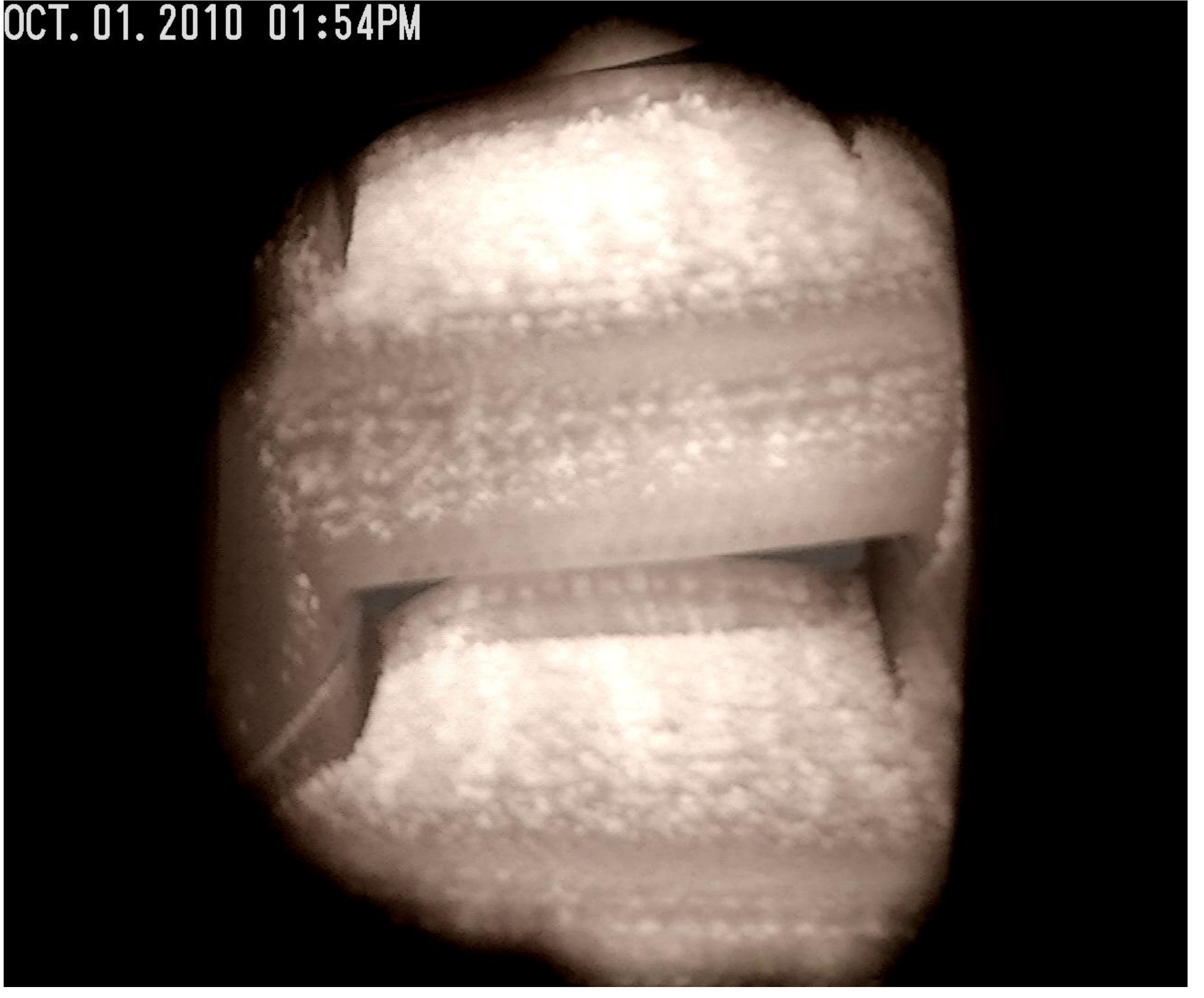

t=+7 min



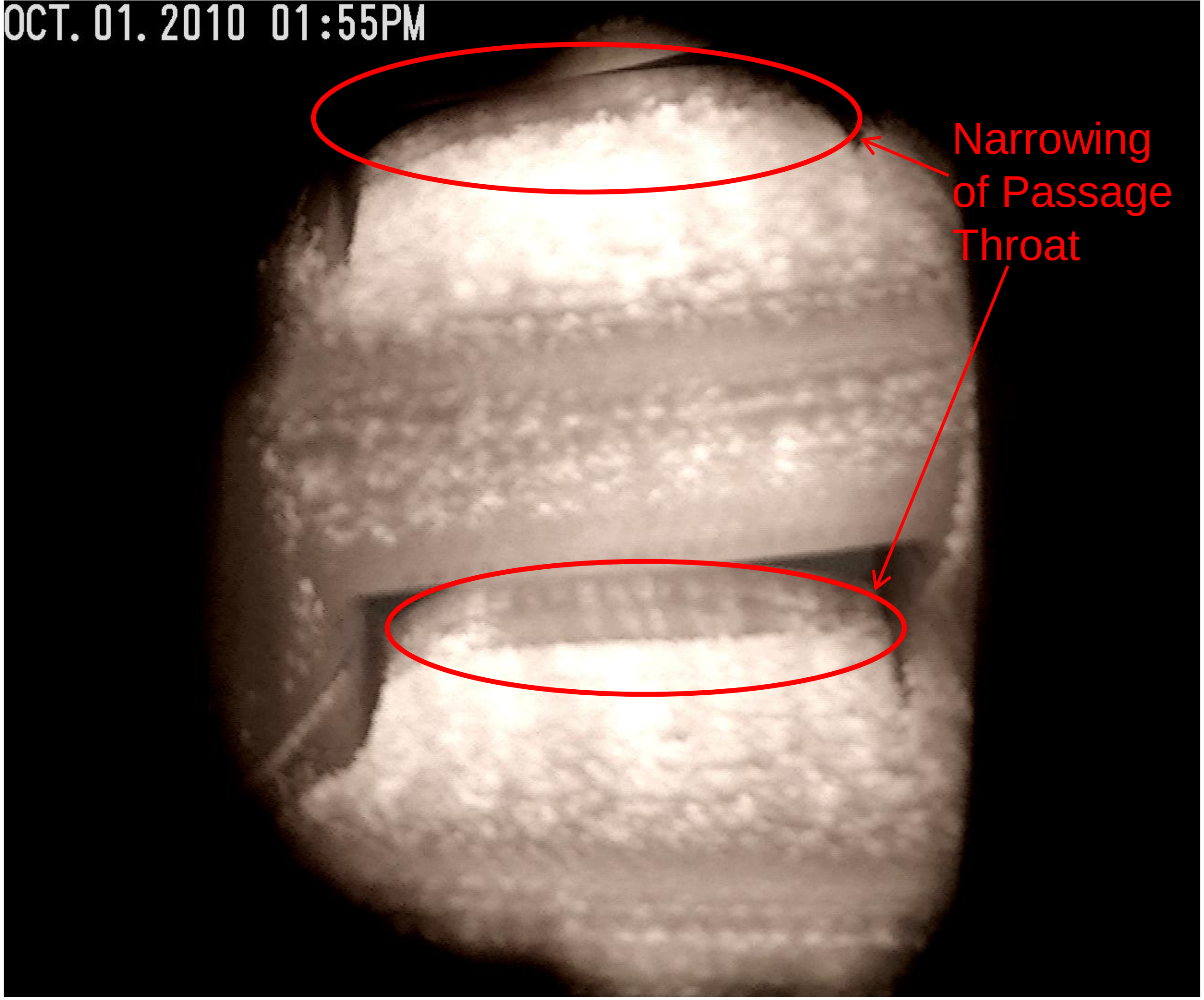

t=+8 min



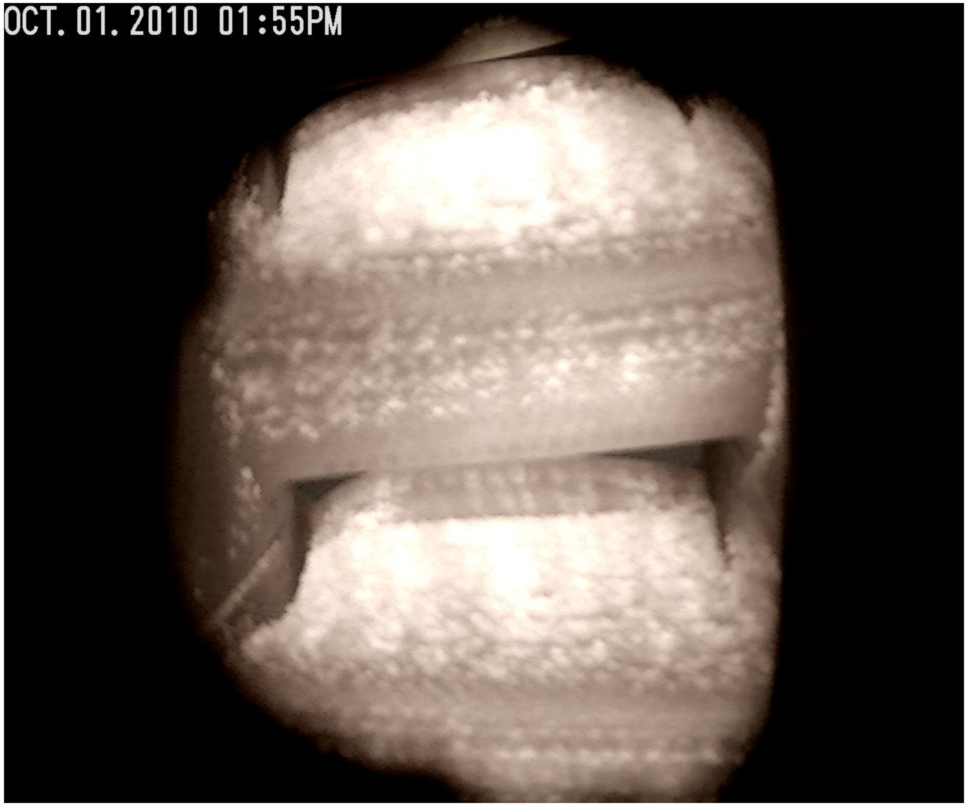

t=+9 min




t=+10 min




t=+11 min




Test on 10/1/10
Wyoming (Jim Bridger Power Station)
Sub-Bituminous Ash (from BYU)
Test Conditions: ~1900 F; M=0.09;
No Film Cooling

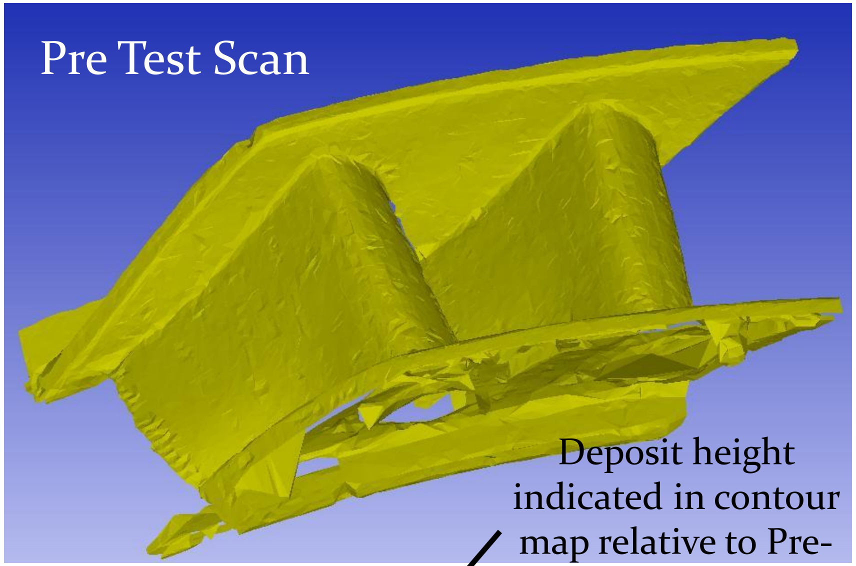
# Final Deposit Image

OBSERVATIONS

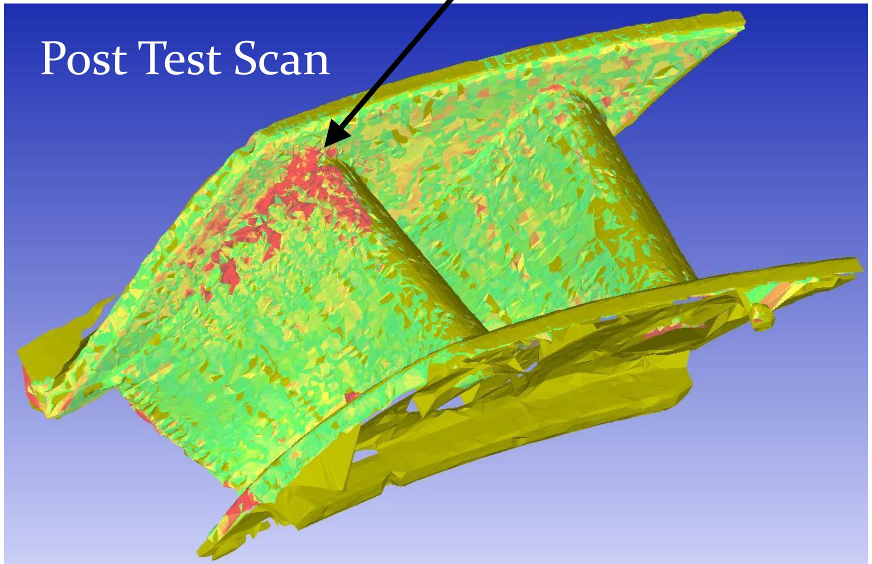
- Deposit builds from mid-chord on pressure surface forward to leading edge.
- Film cooling holes are sites for deposition initiation (whether or not they are blowing)
- Narrowing of passage throat

# Post Test Diagnostics

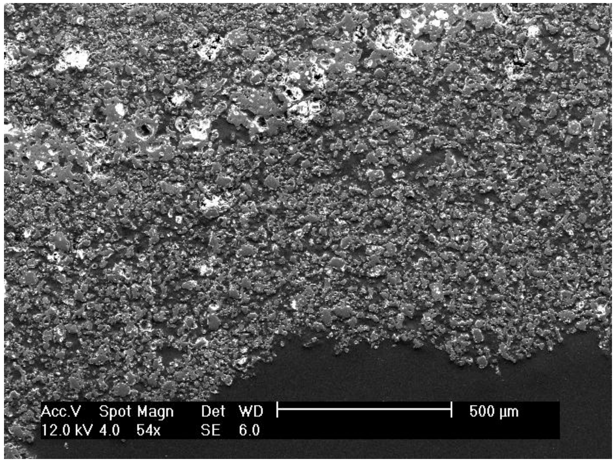
## Surface Metrology

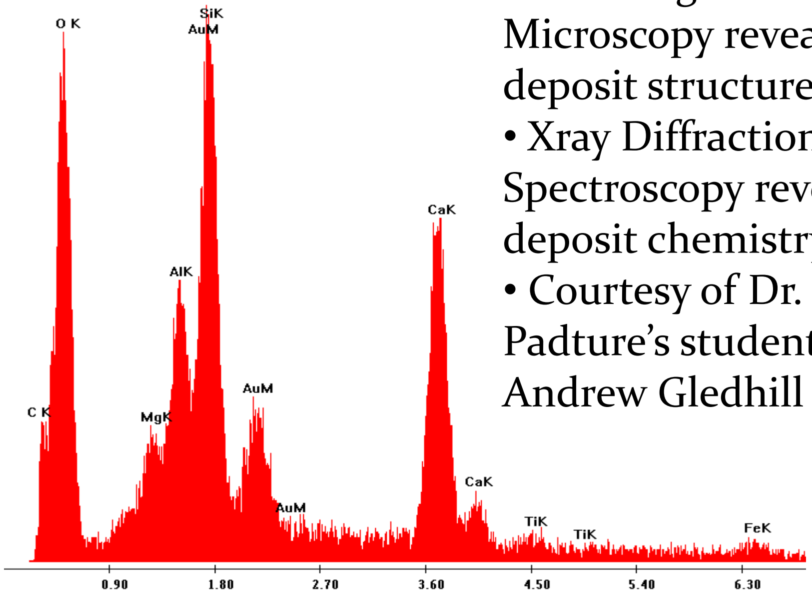



Deposit height indicated in contour map relative to Pre-Test Datum




## Deposit Microscopy




- Scanning Electron Microscopy reveals deposit structure.
- Xray Diffraction Spectroscopy reveals deposit chemistry.
- Courtesy of Dr. Padture’s student, Andrew Gledhill

# TuRFR Results

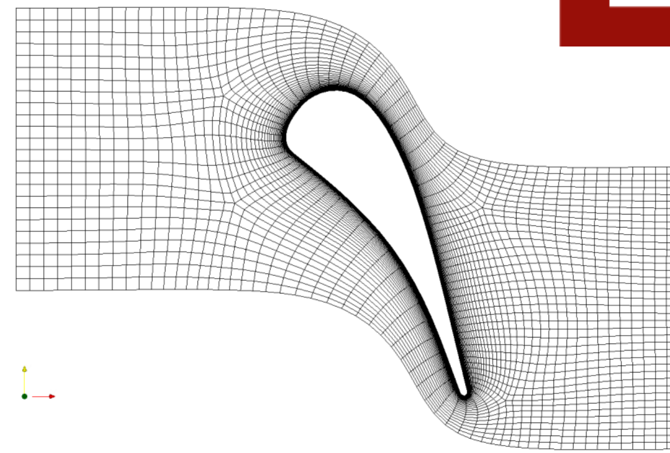
OBSERVATIONS of DEPOSITION MECHANICS

- Suction surface deposit free
- Deposit builds from mid-chord on pressure surface forward to leading edge.
- Deposition is sensitive to ash type and size
- Film cooling holes are sites for deposition initiation (whether or not they are blowing)
- Large deposits are sloughed off the surface during and after testing (e.g. during cooldown)

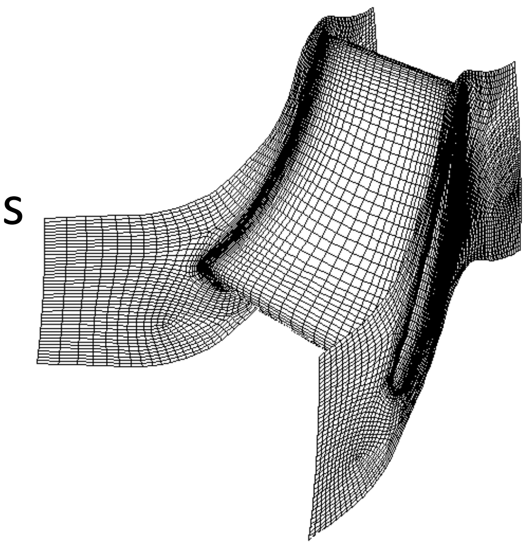
# Ash Deposition Modeling

# Computational Model

- Flow solution using FLUENT
  - Commercially available
  - Solves discretized flow equations to predict fluid dynamics
  - k-ω turbulence model
- Deposition Models
  - developed in C language and incorporated as User-Defined Functions in Fluent
- Turbine grid made using GridPro
  - VKI Turbine Vane
  - GE-$E^3$ Turbine Vane



VKI Turbine Vane (2D)



$E^3$ Turbine Vane (3D)

# Computational Model

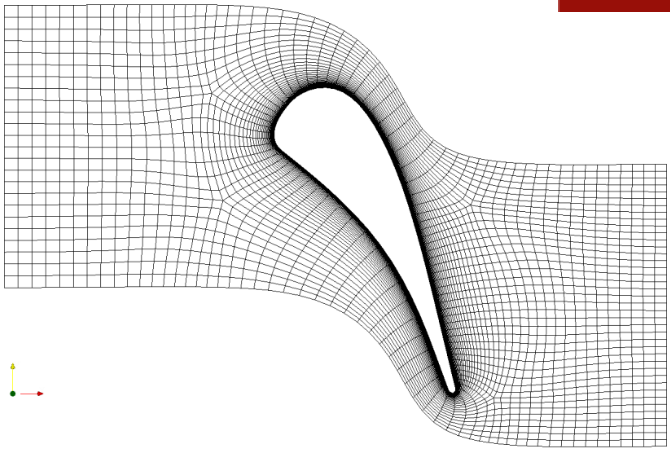
- Two sticking models
  - Critical Viscosity Model (Tafti et al. 2010)
    - Sticking probability based on viscosity of particle

$$P_S(T_P) = \frac{\mu_{Crit}}{\mu_{Tp}}$$

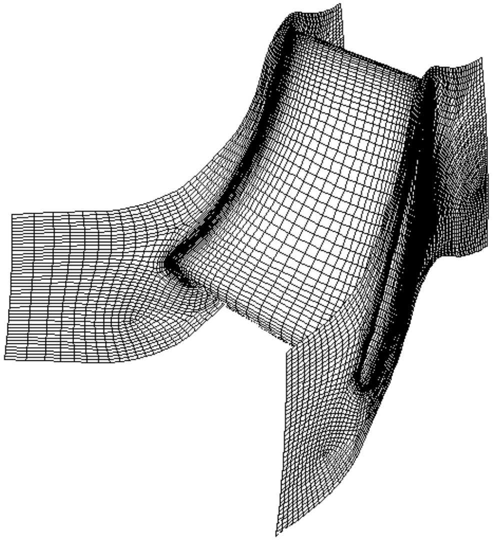
  - Critical Velocity Model

(El Batsh, Haselbacher.2002

- Particles stick if $V_N < V_{CRIT}$
- Particles rebound if $V_N > V_{CRIT}$
- $V_{CRIT} = f(T, d, \ldots)$

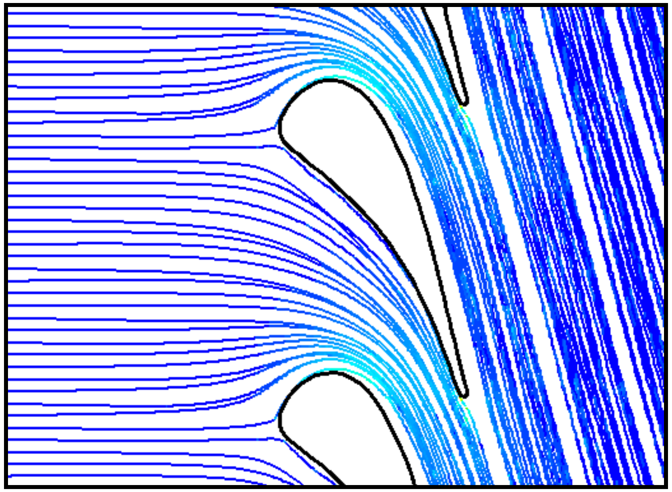


VKI Turbine Vane (2D)

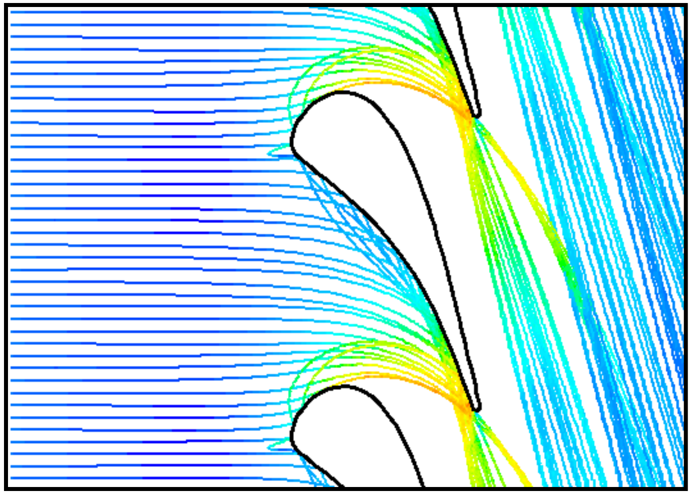


E[3] Turbine Vane (3D)

# Particle Trajectories

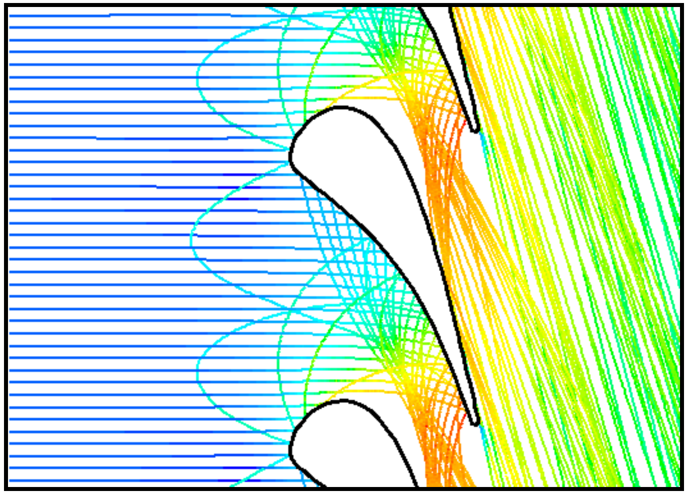


1 μm particles
($St_k$ = 0.01)



10 μm particles
($St_k$ = 1.0)

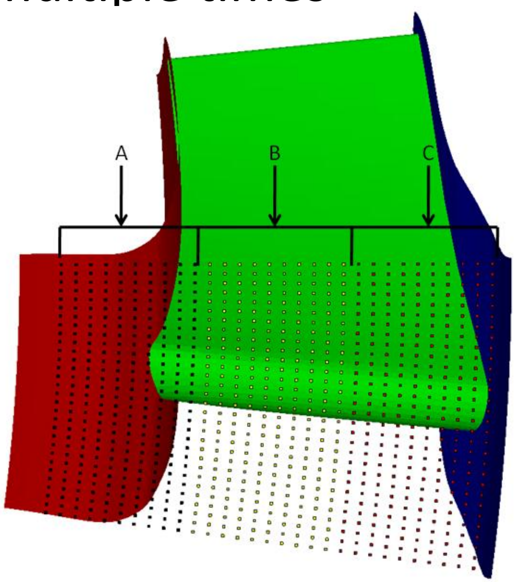
$$St_k = \frac{\rho_p d_p^2 V_i}{18\mu l_c}$$

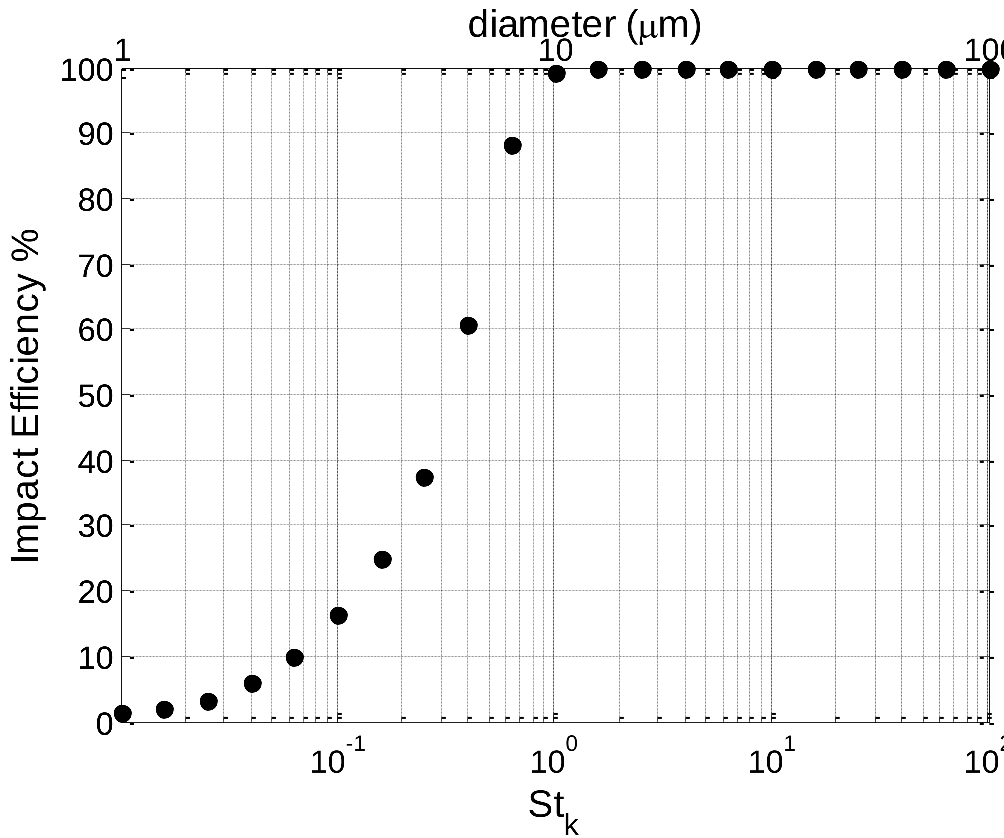


50 μm particles
($St_k$ = 25)

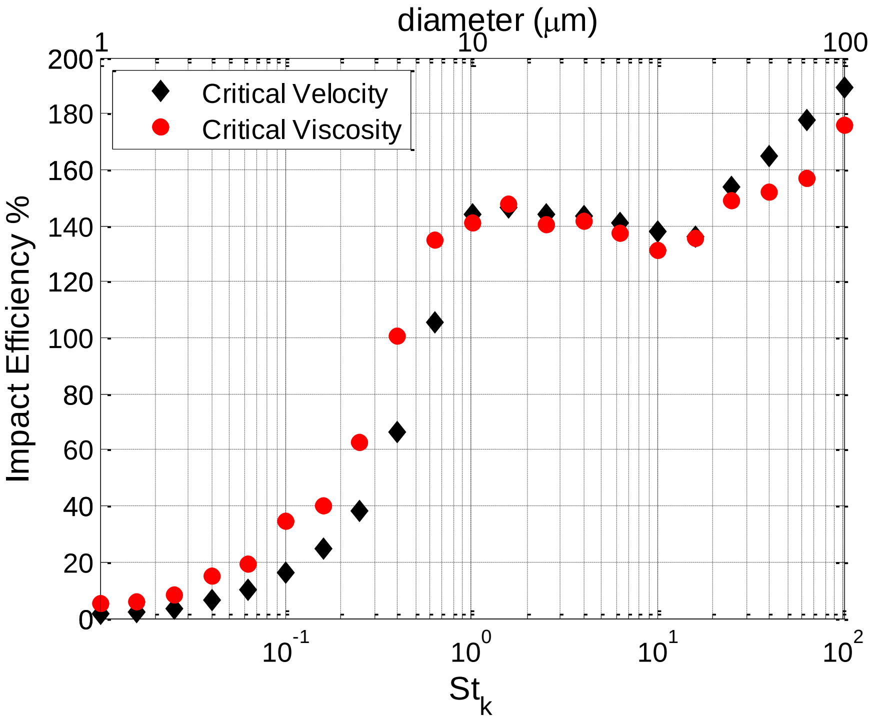
# Simulation Results-Particle Size Effect

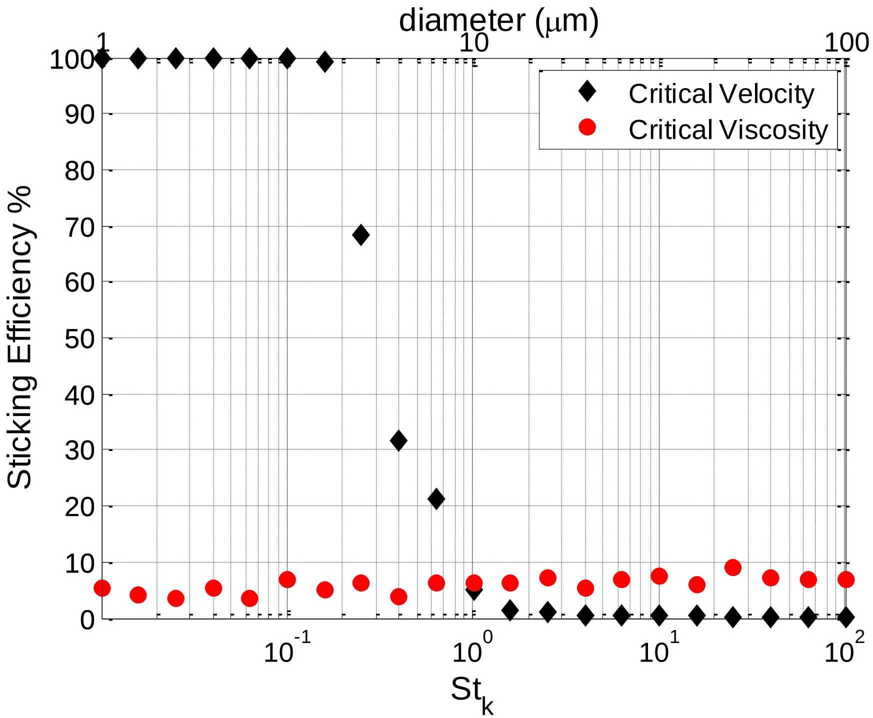
- Small particles less likely to impact surface
- Particles larger than 10 μm ($St_k$ = 1) nearly 100% likely to impact surface
- Particles not allowed to rebound or impact multiple times



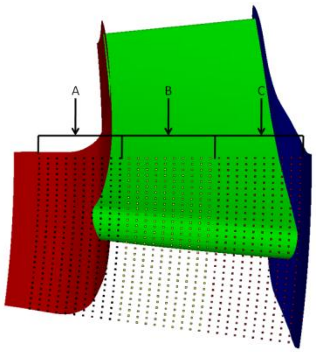



# Simulation Results-Particle Size Effect



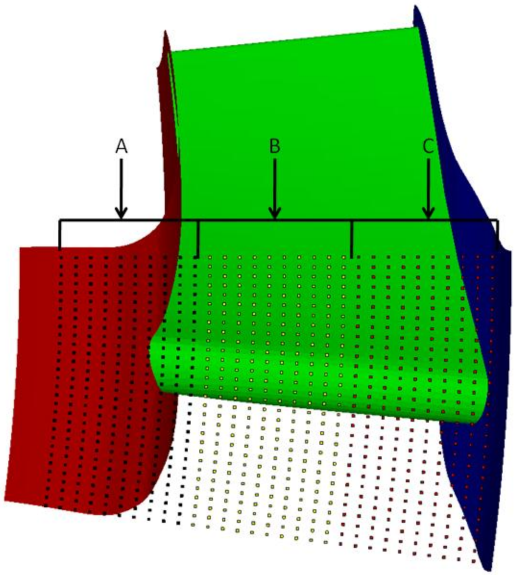



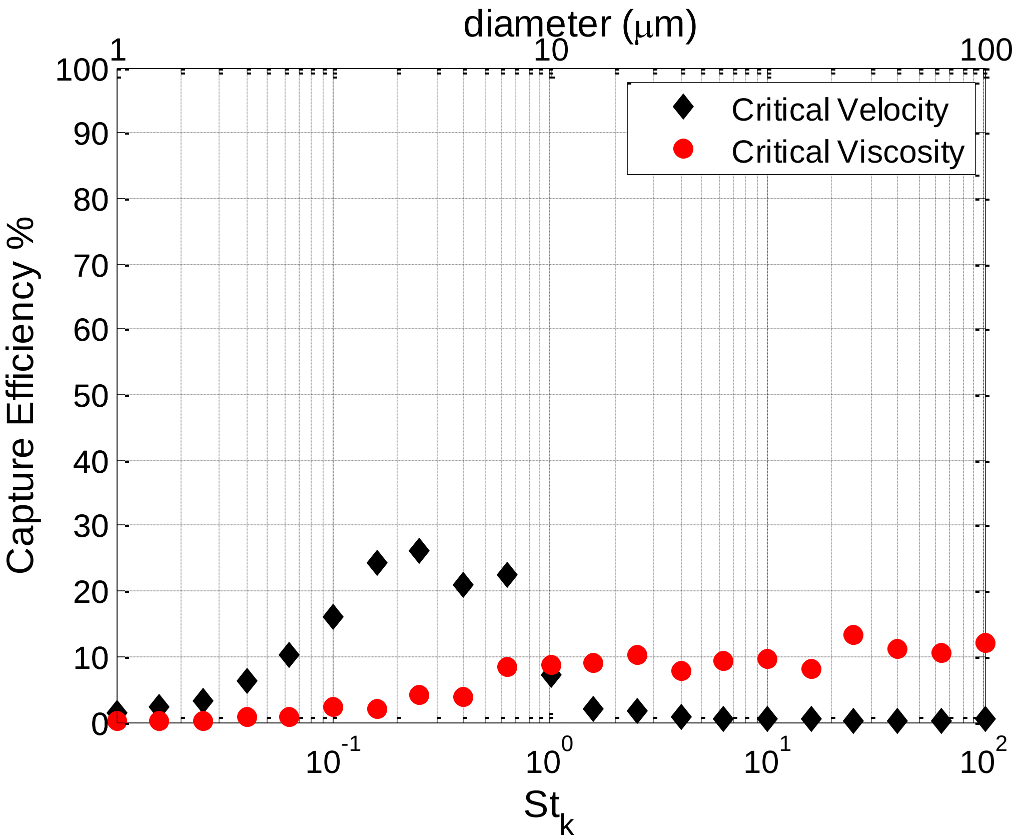

- Multiple impacts allowed
- Impact efficiencies similar for both models
- Large particles impact surface multiple times
- Sticking efficiencies very different for each model



# Simulation Results-Particle Size Effect

- Critical Velocity model predicts range of particles likely to stick ($St_k$ from 0.05 to 1.0)
- Critical Viscosity model predicts larger particles more likely to stick



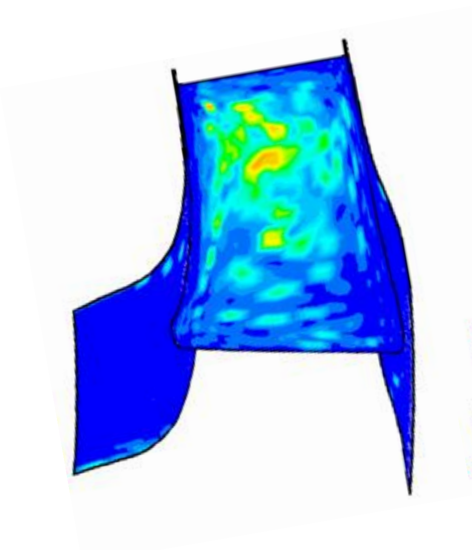



# Simulation Results

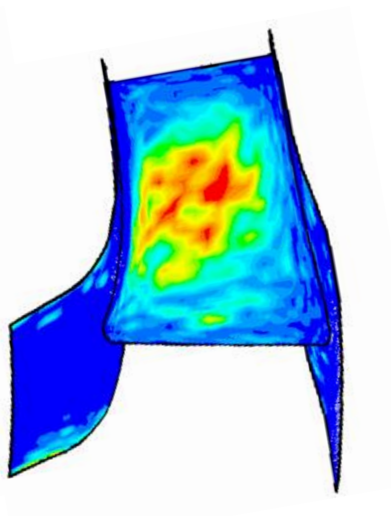
## Comparison of sticking models- JBPS ash

| | Total Injected # | Impact Efficiency % | Sticking Efficiency % | Capture Efficiency % |
|---|---|---|---|---|
| Critical Velocity Model | 18900 | 112 | 10.6 | 12.0 |
| Critical Viscosity Model | 18900 | 124 | 6.2 | 7.7 |
| Experimental | - | - | - | ~20.0 |

Critical Viscosity



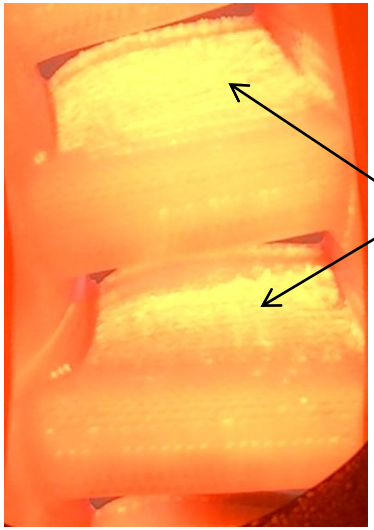
Critical Velocity



Experimental

Post test

Initial Deposit



Deposit

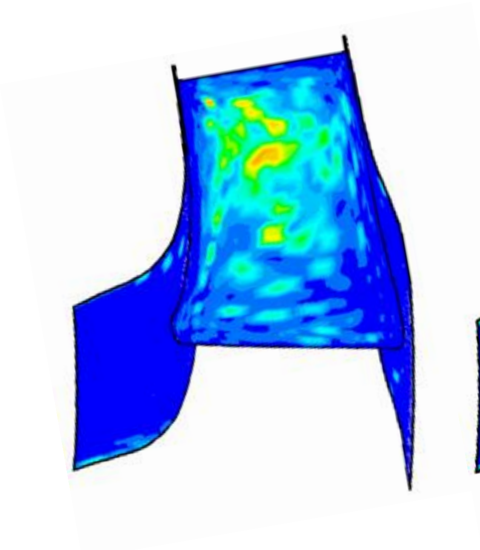
# Simulation Results

## Comparison of sticking models- JBPS ash

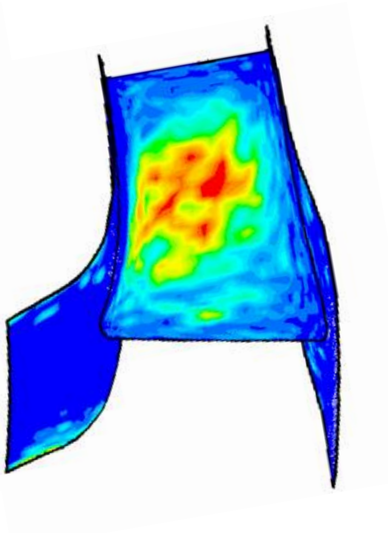
- Both models predict deposition on pressure surface at mid chord
- Both models underestimate deposition, especially viscosity model (with defined sticking temperature)
- Model is most accurate at predicting initial deposition

Experimental

Critical Viscosity

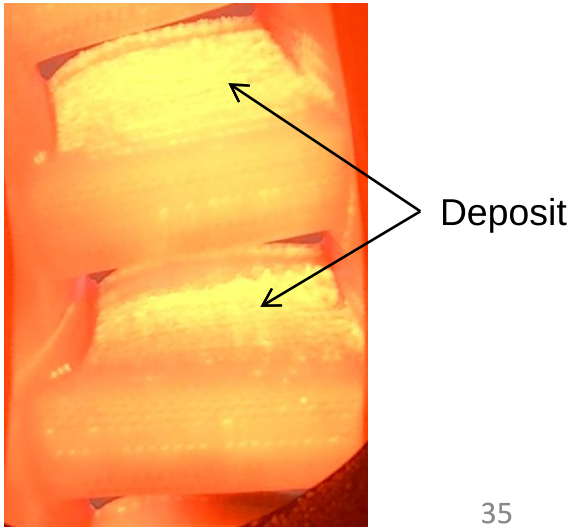


Critical Velocity

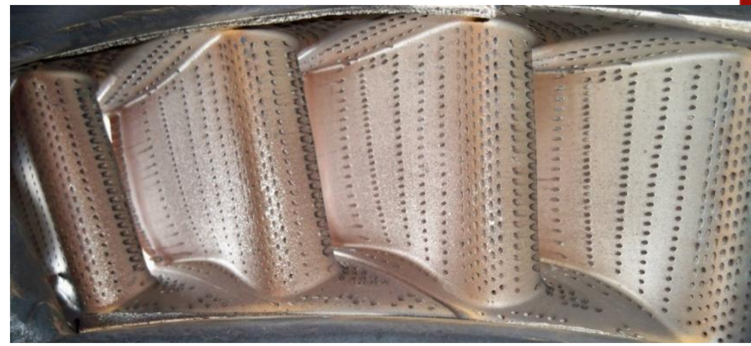


Post test

Initial Deposit



# Experimental Results – Four Ash Types



Bituminous

Little Deposition

JBPS Sub-bituminous

Much Deposition

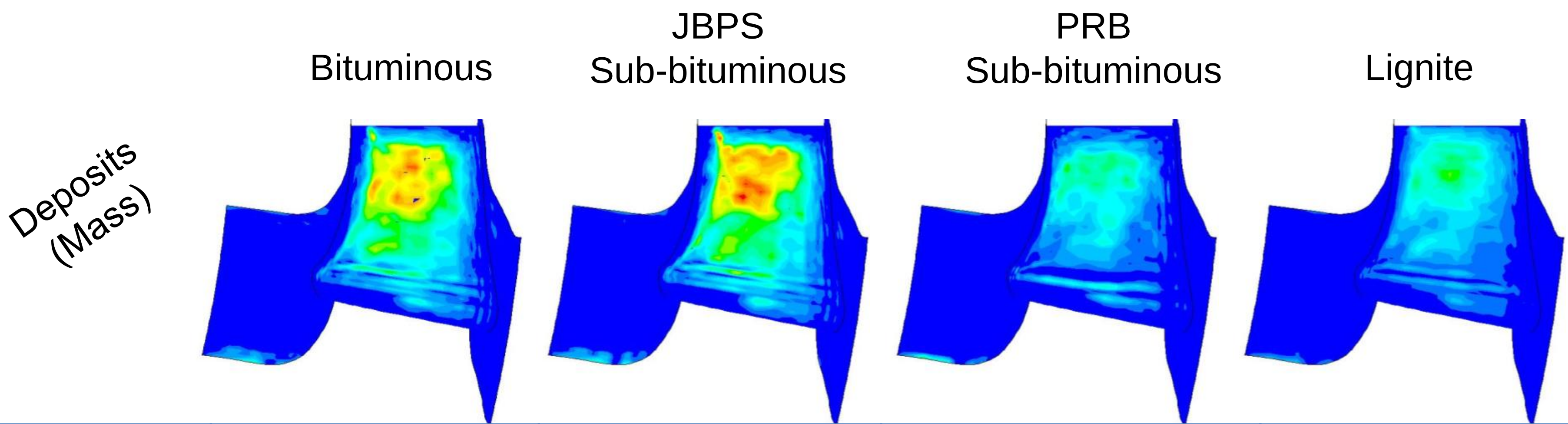
PRB Sub-bituminous

Much Deposition

Lignite

Most Deposition

# Deposit Results- Four Ash Types



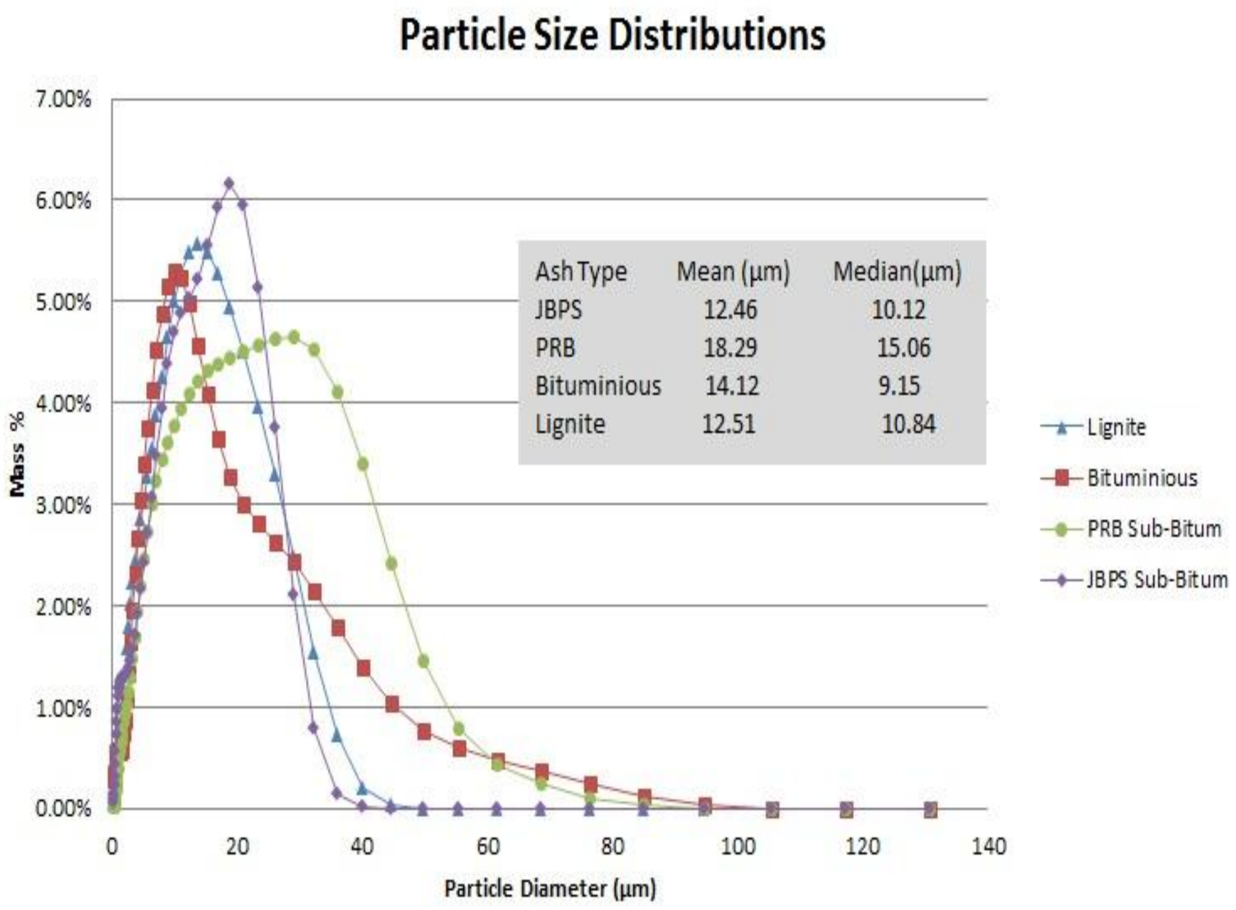

| % of Mass Captured | 8.2% | 7.7% | 6.2% | 6.8% |
|---|---|---|---|---|

- Numerical simulations did not correspond well with experiments using critical viscosity model
- All predicted similar deposition patterns but with varied magnitudes
- Assumed same sticking temperature for all ash types

# Ash Size Measurements

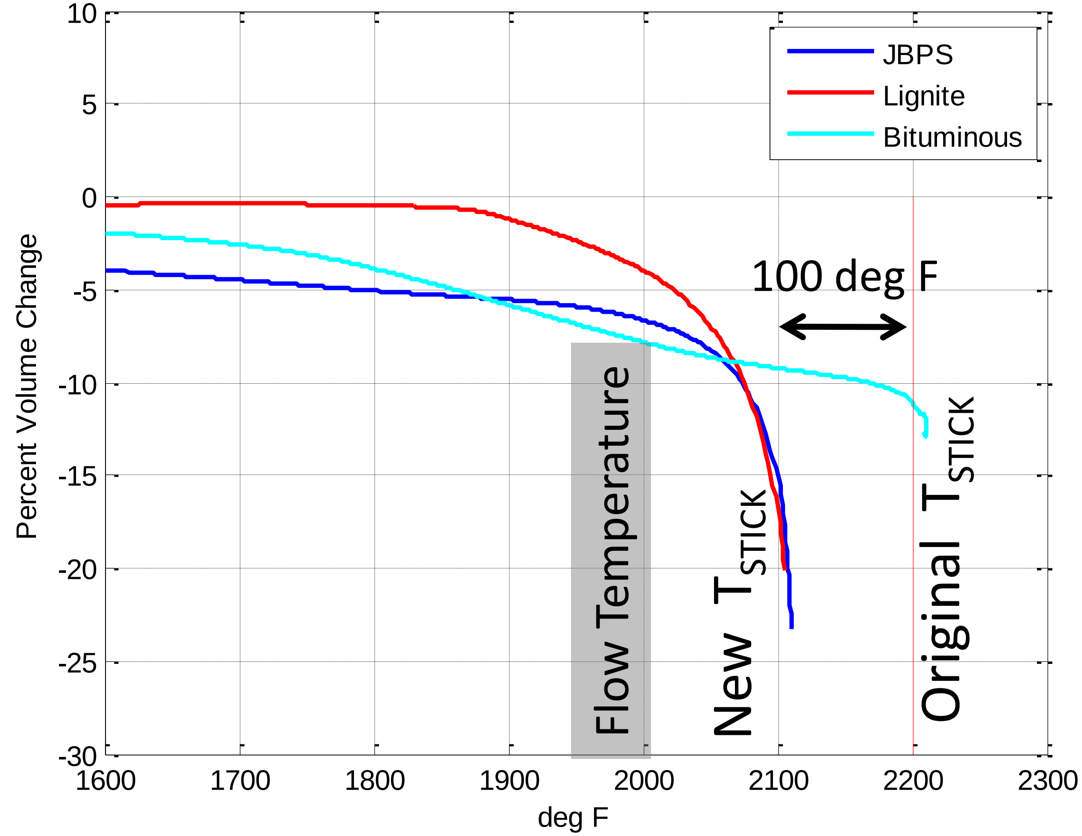
- Similar size distributions, with exception of PRB sub-bituminous
- Larger PRB distribution increases expected distribution in model.
- Verified ash densities

$$St_k = \frac{\rho_p d_p^2 V_i}{18\mu l_c}$$



# Ash Thermal Expansion Measurements

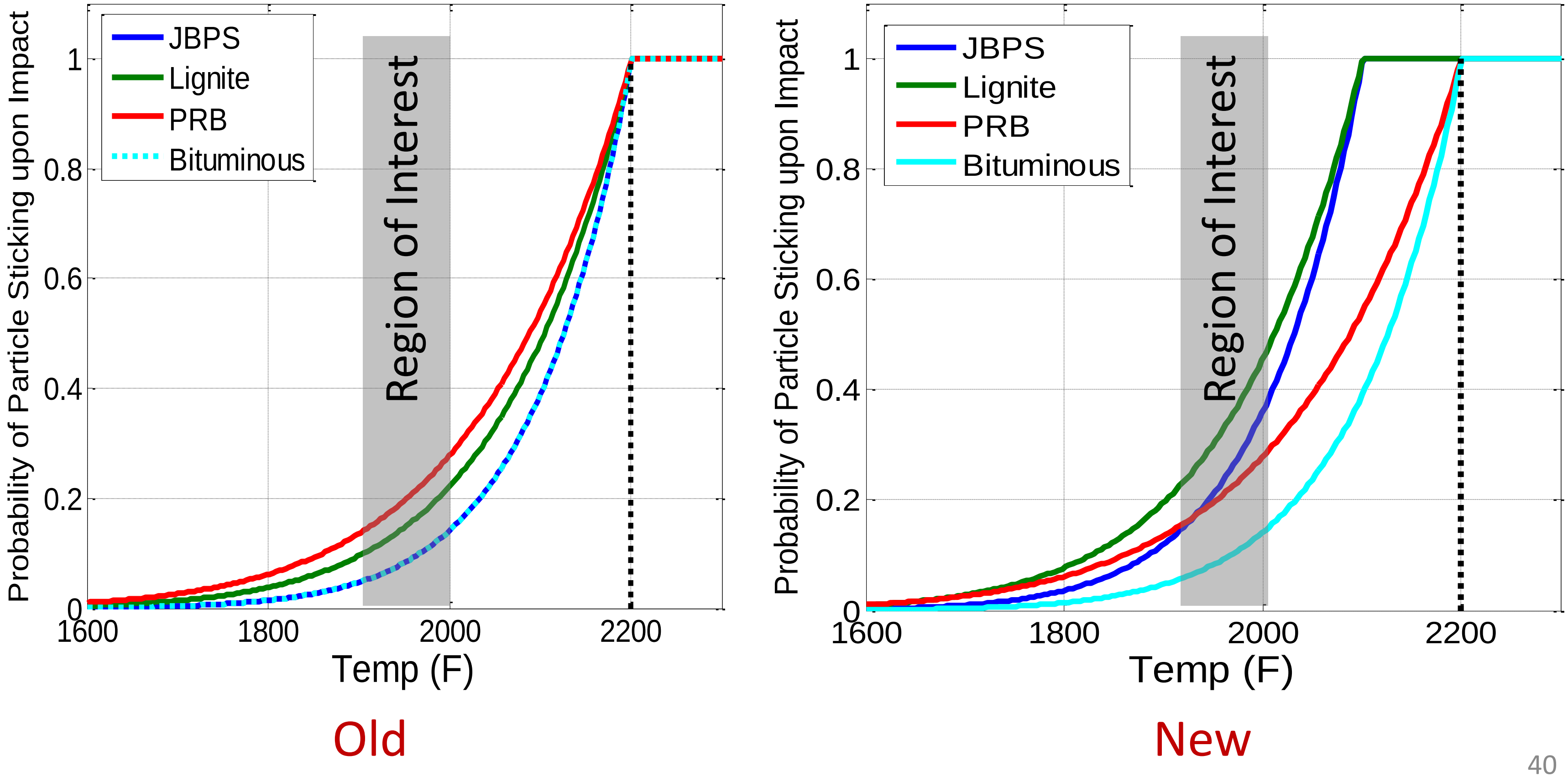
- Graph shows thermal expansion with increasing temperature. As ash particles sinter and melt, the volume of the ash decreases.
- JBPS and Lignite begin melting at 2100 F
- Bituminous begins melting at 2200 F
- These values are used as critical sticking temperatures
- PRB ash failed test



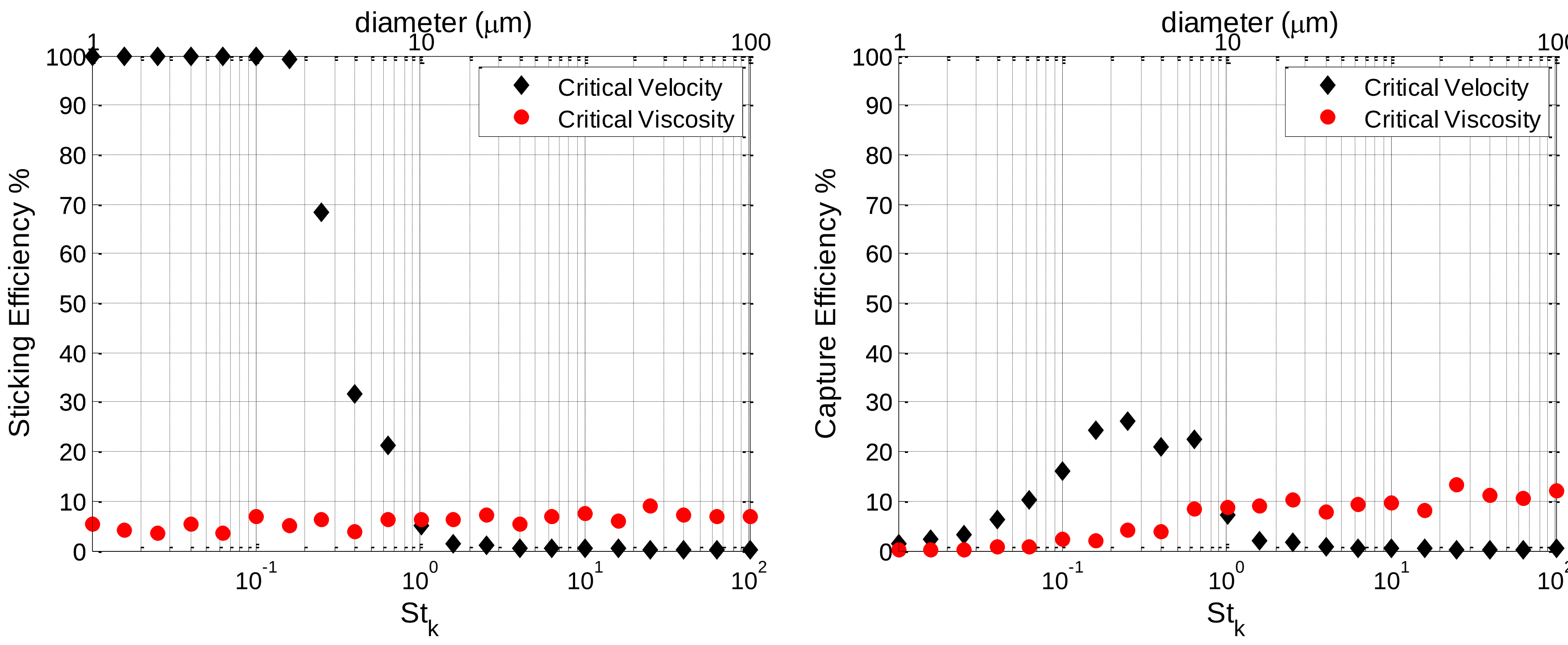

$$P_S(T_P) = \frac{\mu_{Crit}}{\mu_{Tp}}$$

# Sensitivity to Ash Composition

- Sticking Probabilities for Critical Viscosity model
- Adjusted sticking temperature better agrees with experimental results

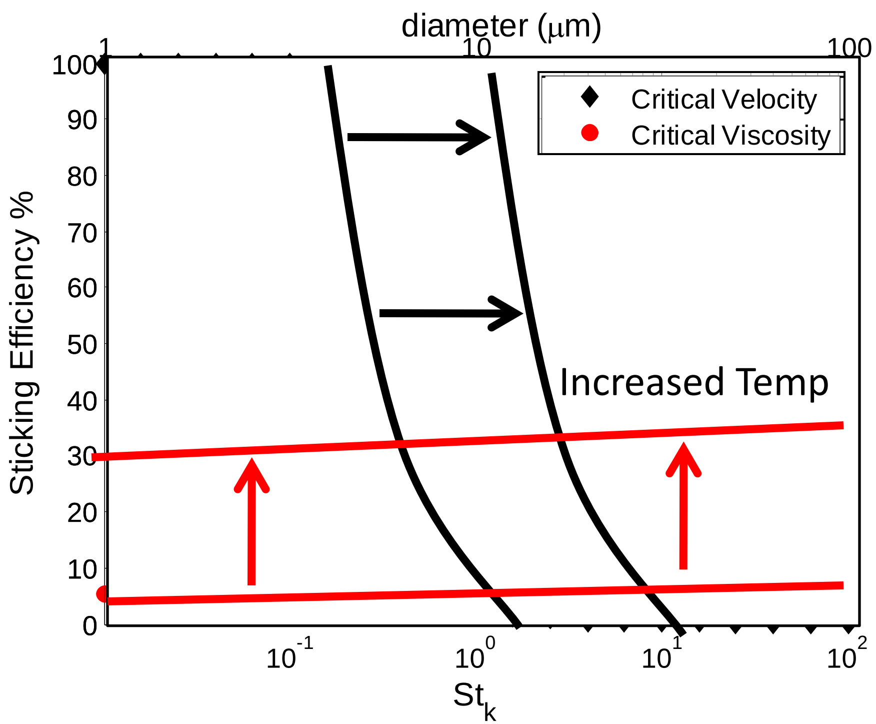


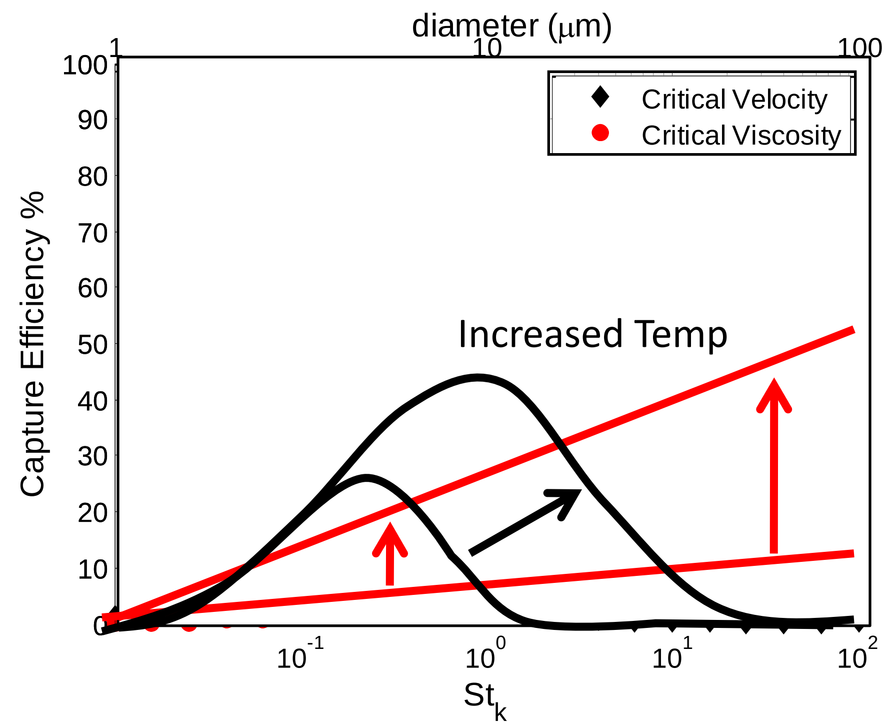
# Sensitivity to Ash Composition




- Plots <u>only</u> valid for assumed μ(T) [critical viscosity] or E(T) [critical velocity] relationship.

# Simulation Results – Temperature Sensitivity



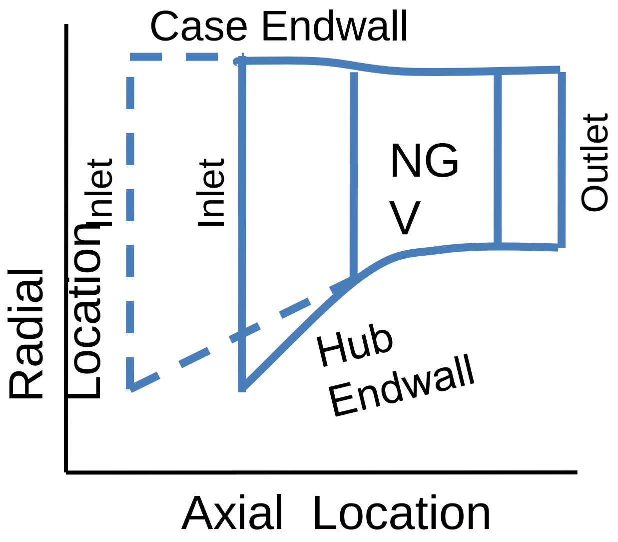



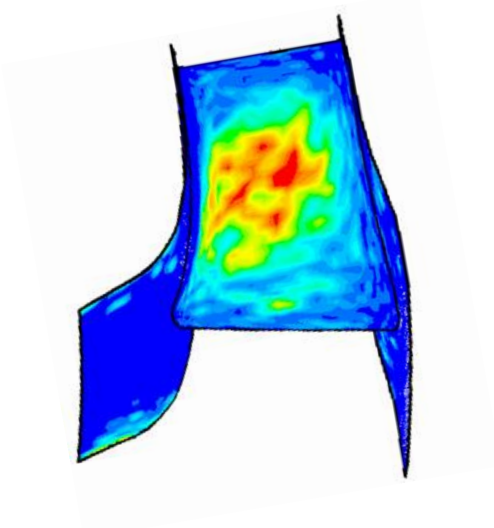

- Higher fluid temperatures, or lower critical sticking temperature, increases probability of sticking and deposit
- Viscosity model sensitive to critical sticking temperature
- Viscosity model more closely matches experiment

$$St_k = \frac{\rho_p d_p^2 V_i}{18 \mu l_c}$$

# Endwall Modifications

- Particles deposited preferentially toward hub endwall
- Hub endwall was redesigned with less severe inlet angle

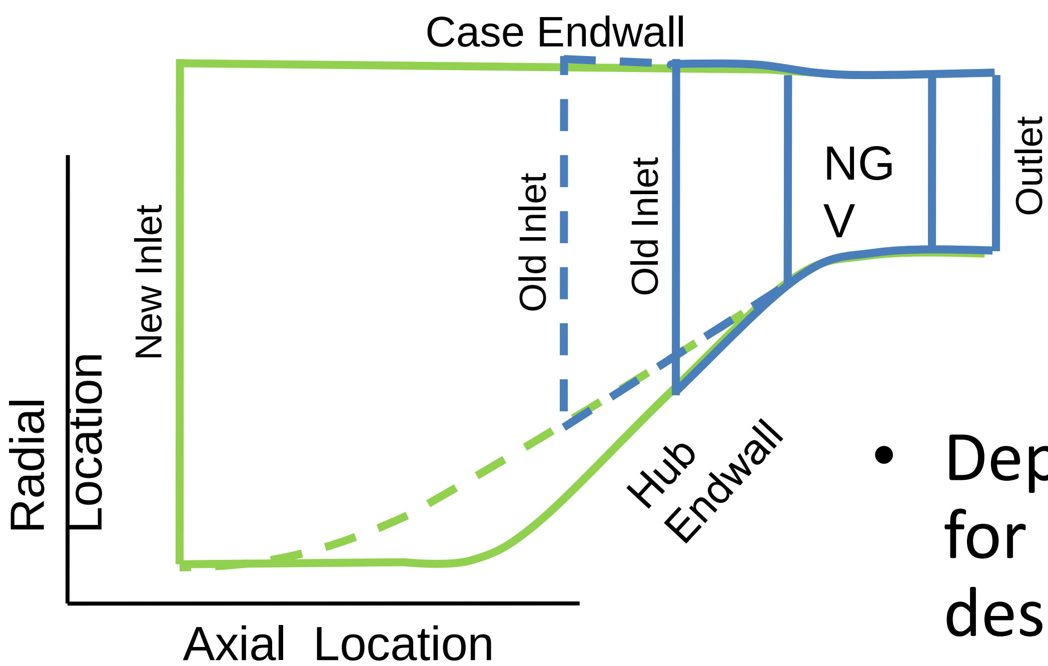


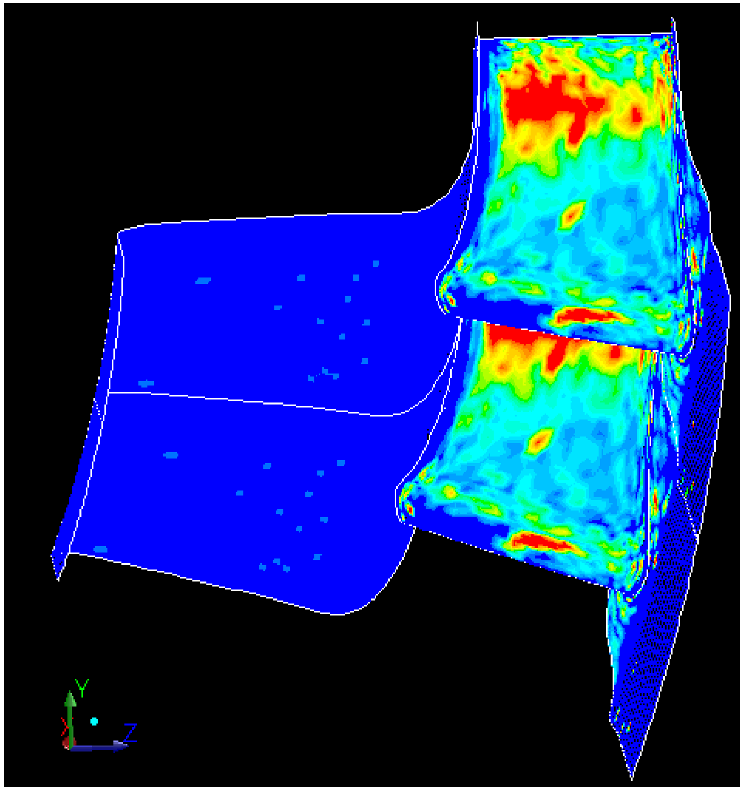



- Results showed slight difference in deposition rates
- Difference likely due to extended inlet boundary condition affecting passage flow fields, rather than endwall modification

# Endwall Modifications

- Endwall extended upstream
- Inlet planes identical
- Allowed for more realistic turbulent dispersion of particles

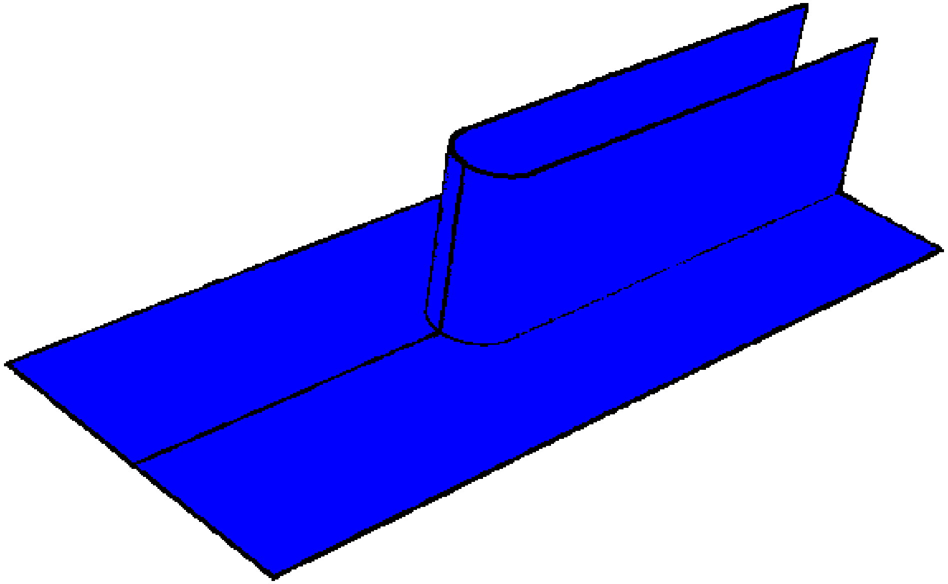


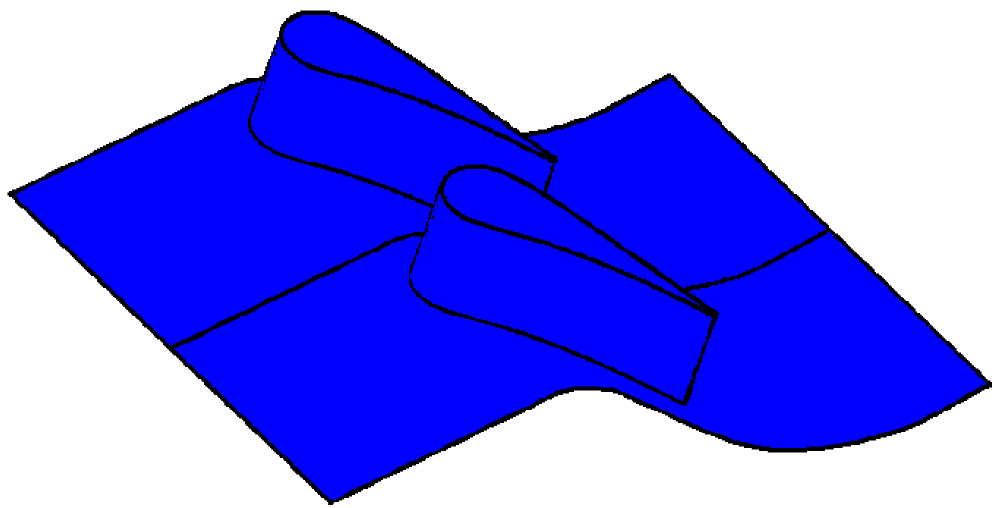




- Deposition rates identical for both extended endwall designs

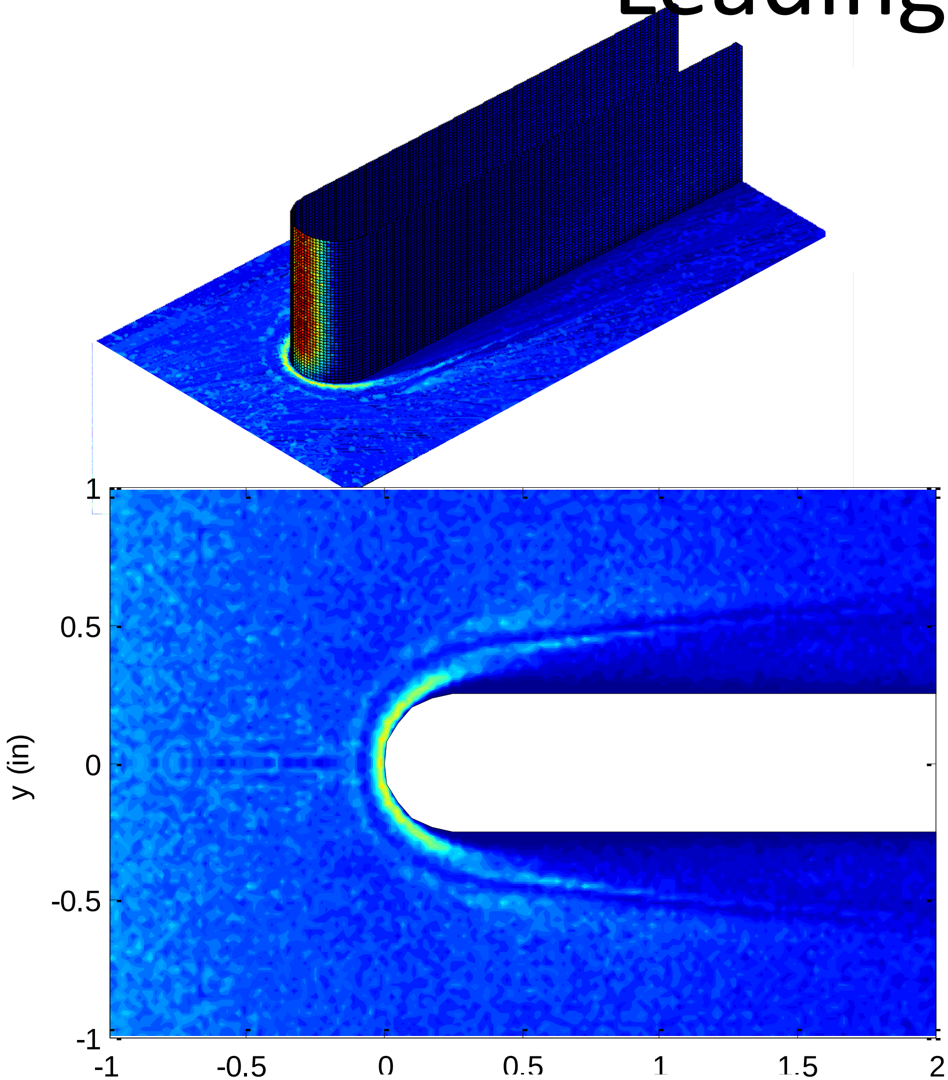
# Flat Endwall Studies

- Investigate how particulate deposits on endwalls.
- Ran tests using a flat plate with a cylindrical leading edge
- Rolls Royce high pressure vane with flat endwalls

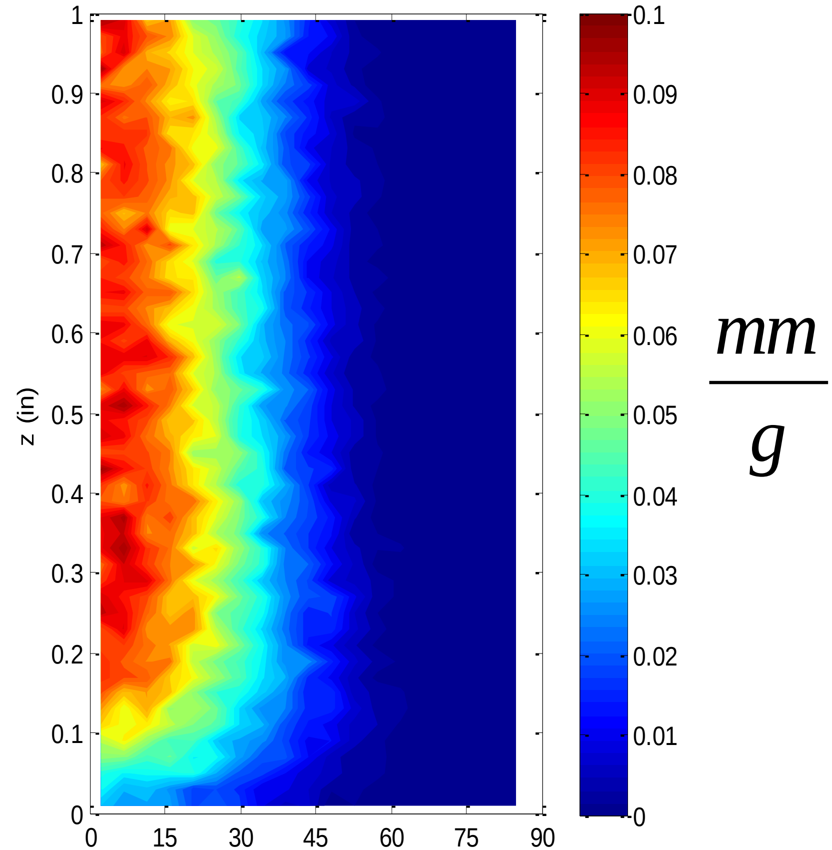




# Flat Endwall Studies – Flat Plate Leading Edge



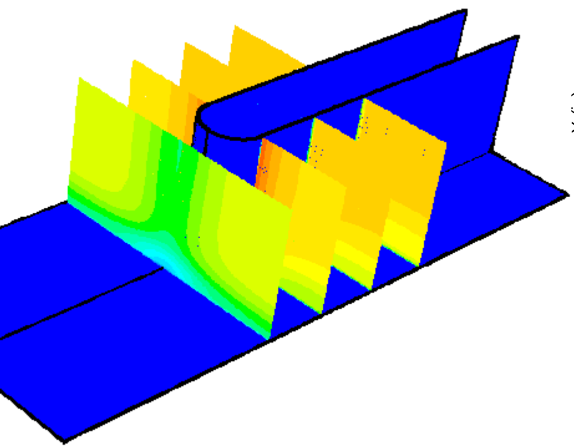

Endwall Deposition

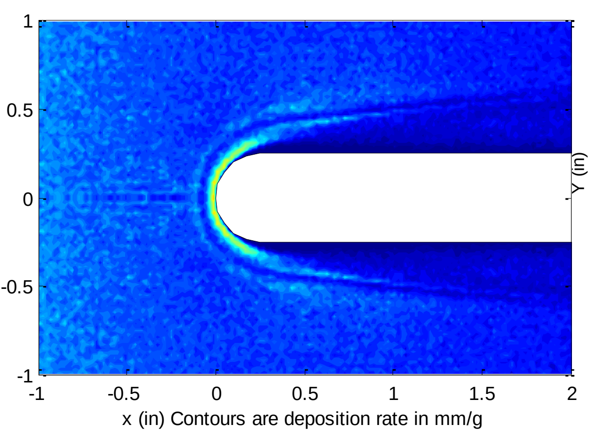


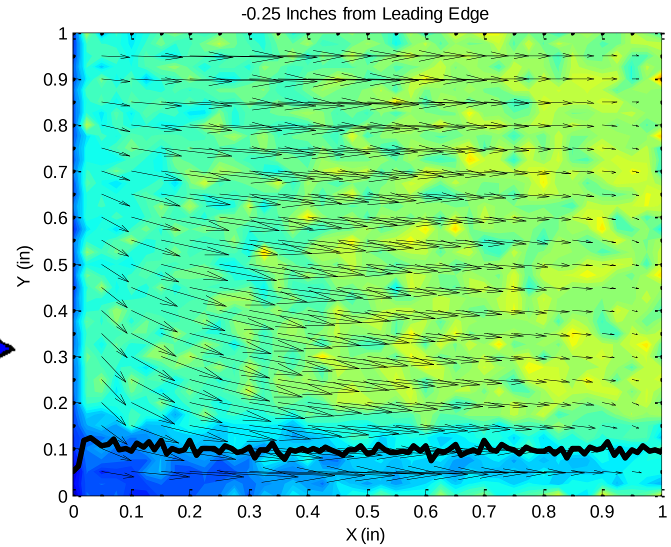

Leading Edge Deposition (by angle)

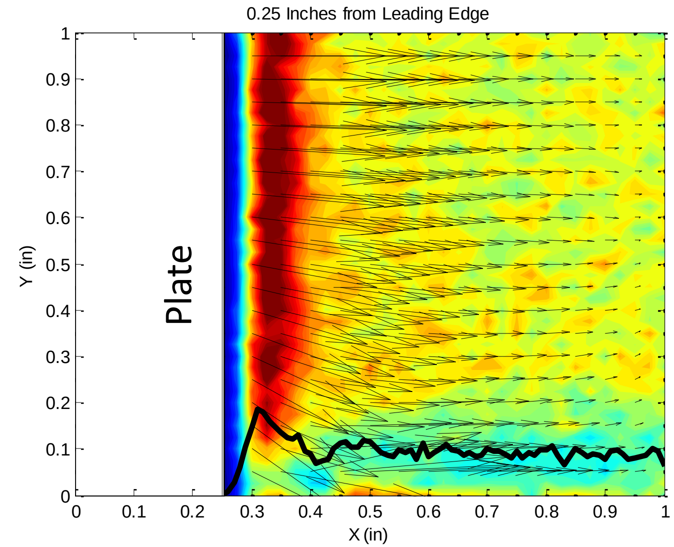
5 micron Particles, $St_k$ = 0.25 Re = 12.7K

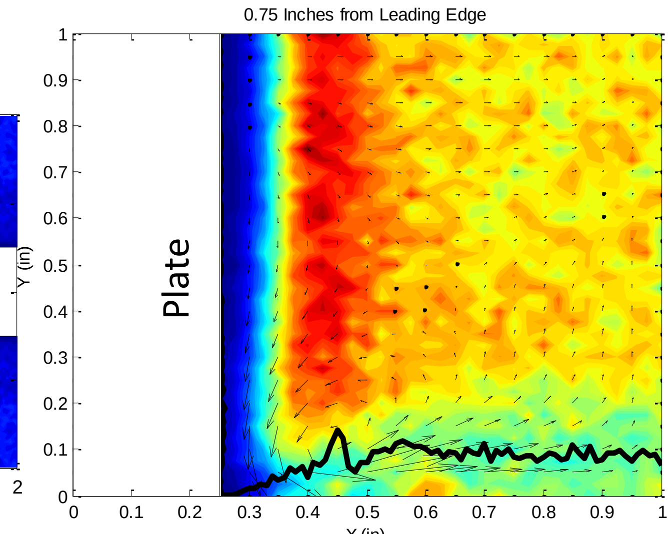
# Flat Endwall Studies – Particle Concentration

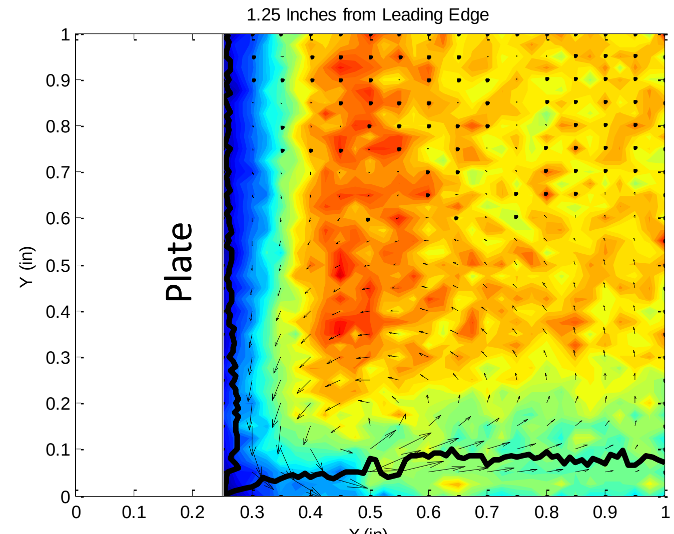




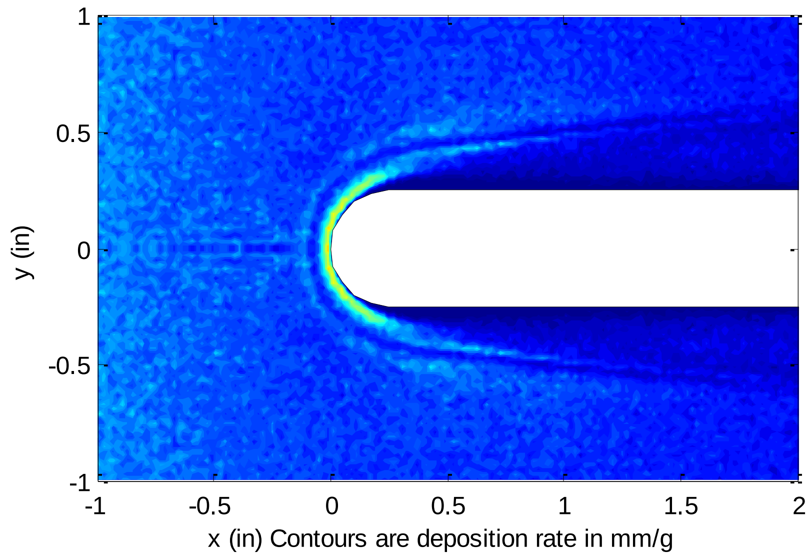



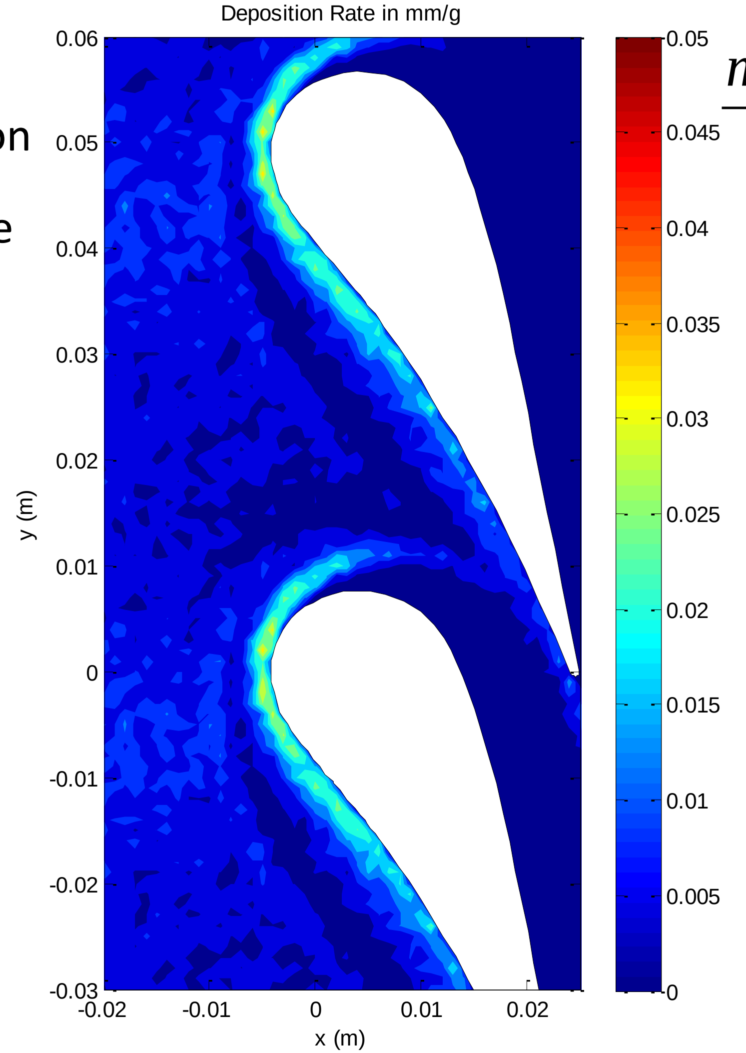



# Flat Endwall Studies – Vane Endwall

- Largest Deposition rates near leading edge.
- Even these deposition rates on endwalls are generally less than half of the magnitude of deposition on leading edges (or pressure surface).
- Larger particles responsible for deposition on vane surfaces. Alternatively, smaller particles are more susceptible to deposit on endwalls.
- Vane deposition dominated by inertial impaction. Endwall deposition due to turbulent dispersion, secondary flows, or particle concentration.



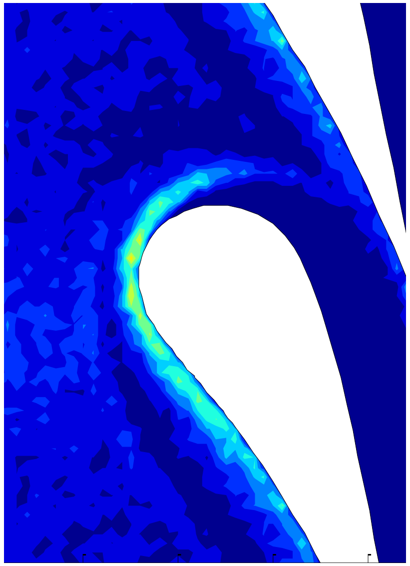



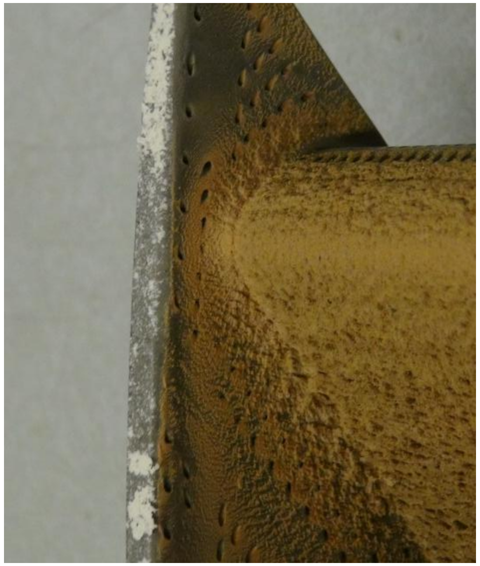

$\frac{mm}{g}$

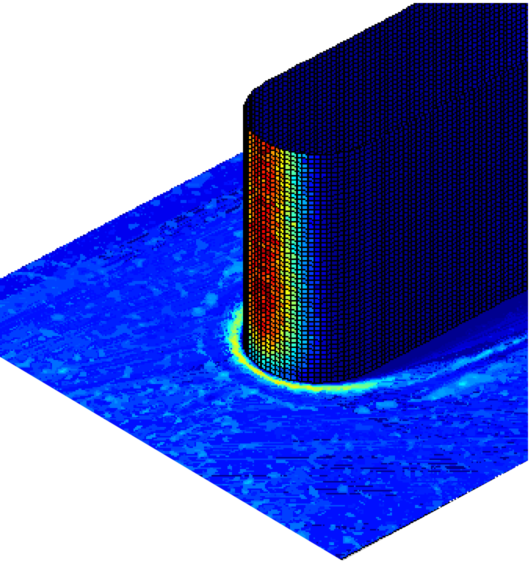
5 micron Particles, $St_k = 0.25$ Re = 12.7K

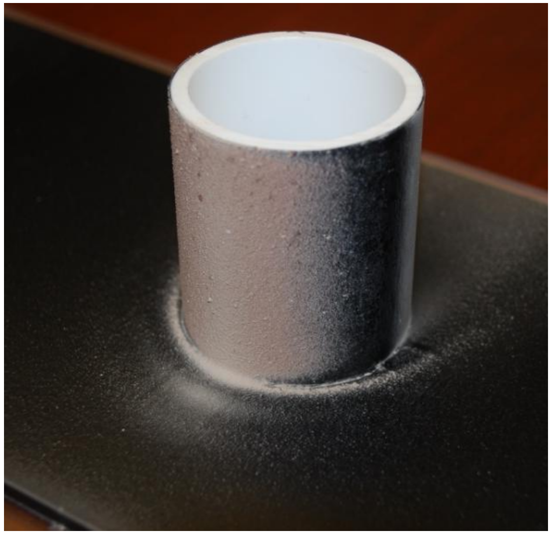
# Flat Endwall Studies – Comparison with Experiments

- Leading edge endwall deposition and secondary flow patterns observable in experiments, especially with low $St_k$ number
- Endwall deposition minor compared to leading edge.

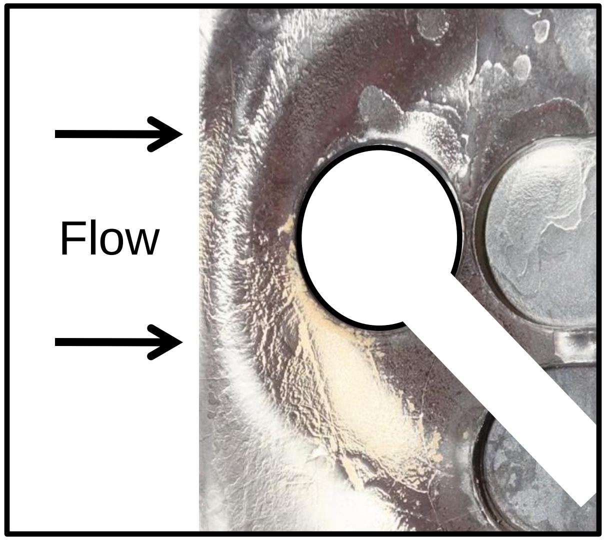






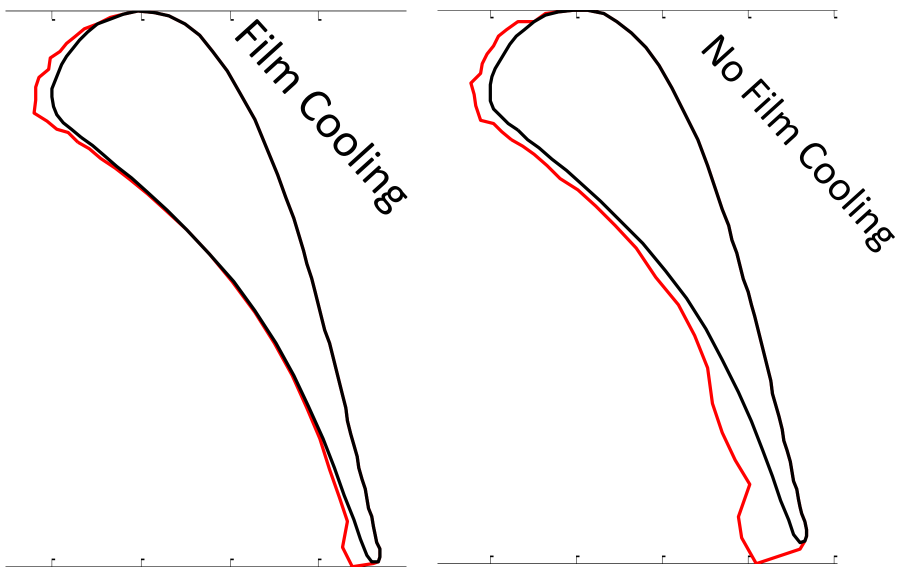


Lawson, Thole (2011)

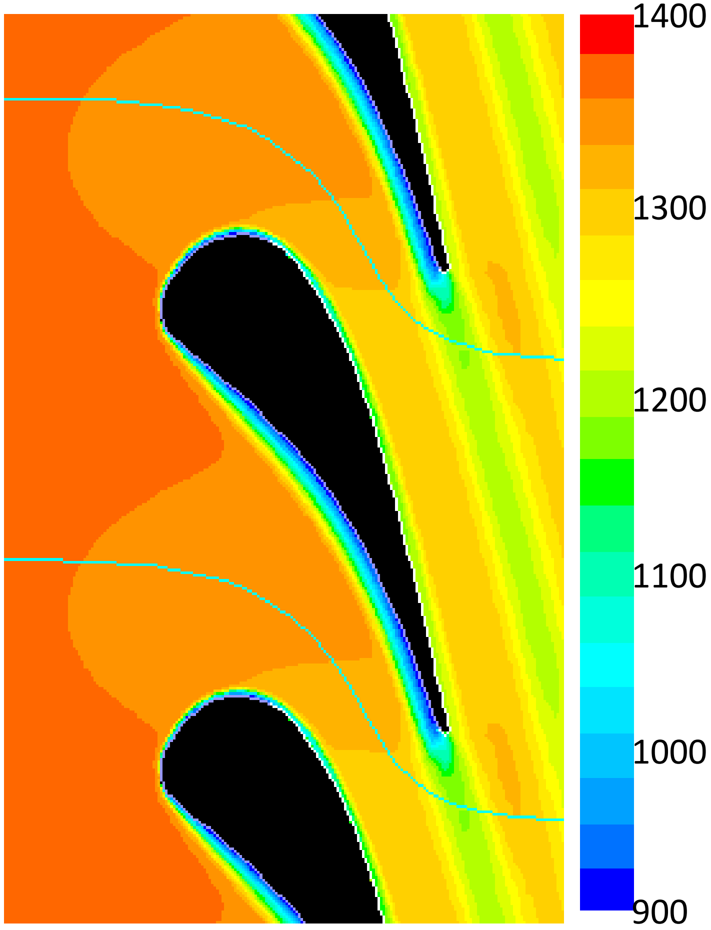



Faired Cylinder TuRFR test

# Film Cooling –Transpiration Cooling




- Film cooling reduced deposition by 80% for 6 μm diameter particles
- Reduced trailing edge deposition for small $St_k$ particles, but not as much as is seen in experiments.
- Little change for large $St_k$

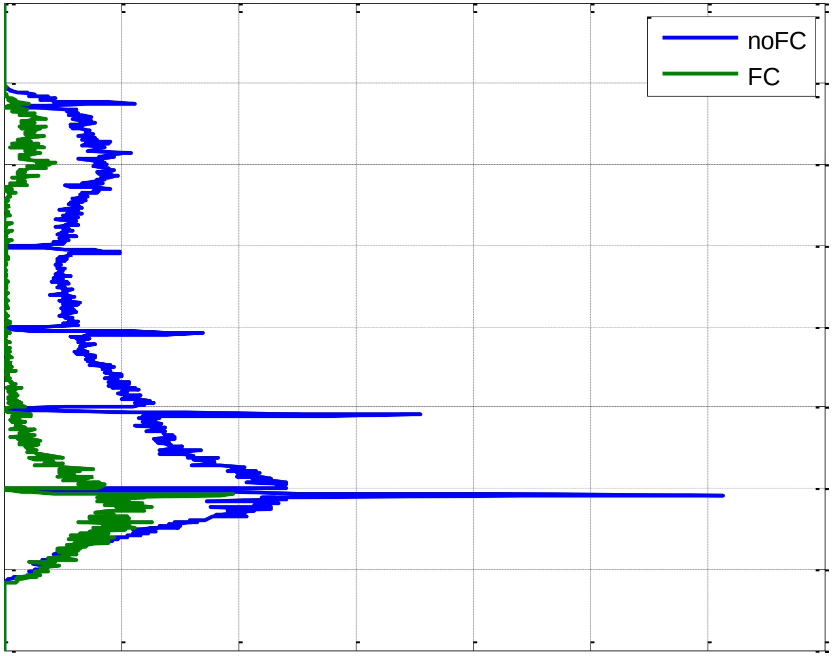


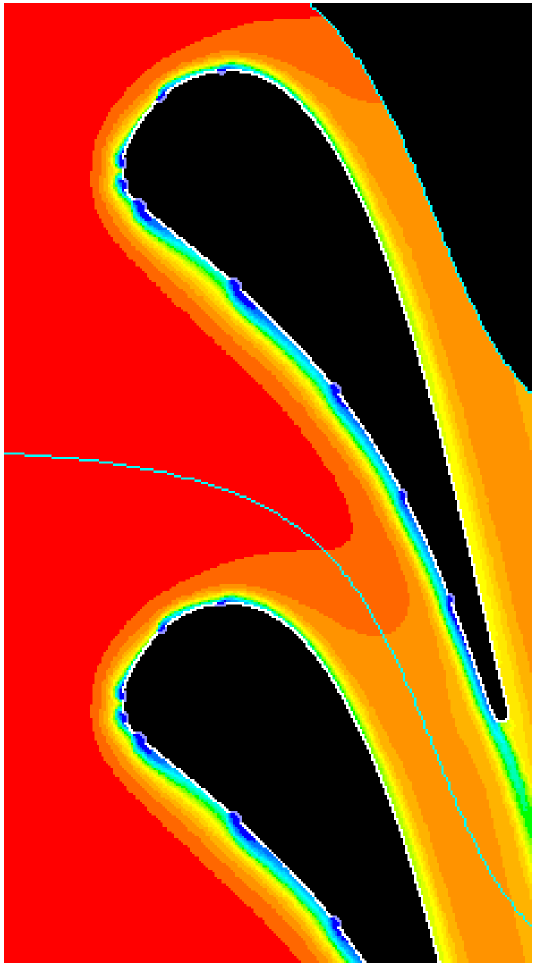

Temperature (K)

# Film Cooling – Slit Cooling

- Similar results as transpiration cooling
- Leeward side of film cooling "holes" are sites for much larger deposition rates.
- Average deposition not significantly changed in hole locale
- Same limitations as transpiration cooling.

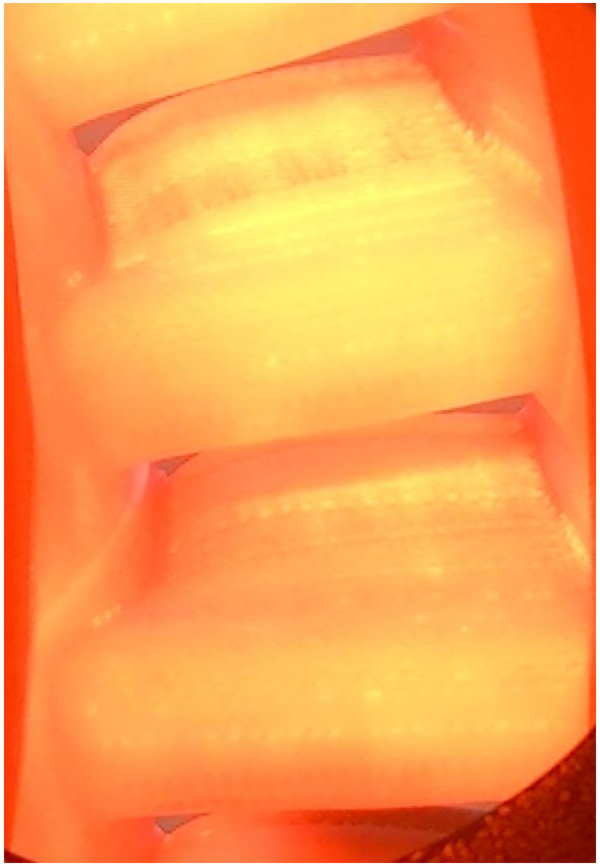
Deposit histogram on tangential direction 10 $\mu m$



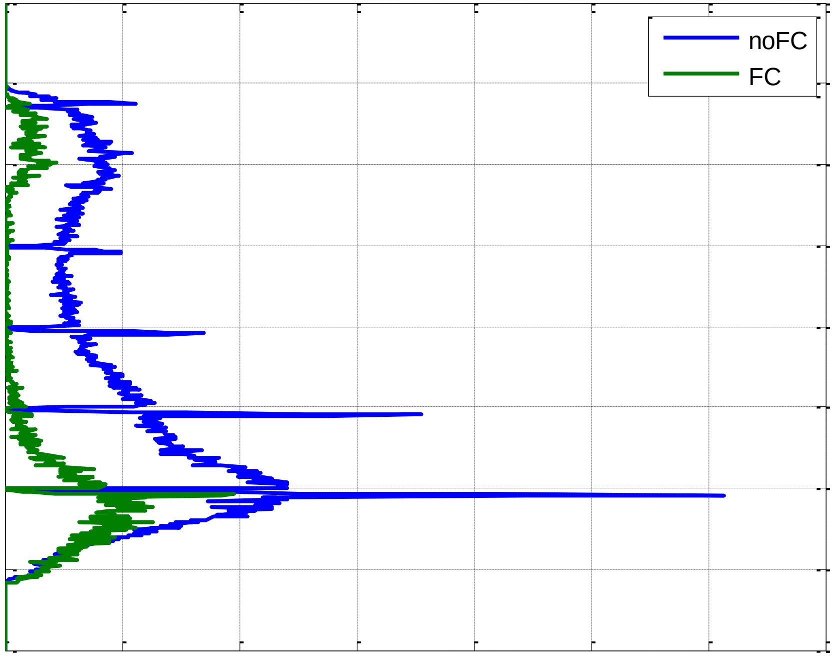



# Film Cooling – Slit Cooling

- Experimental tests indicate that deposition begins in film cooling holes, even when film cooling is present



Deposit histogram on tangential direction 10 μm



# Effect of Stokes Number and Film Cooling on Deposition

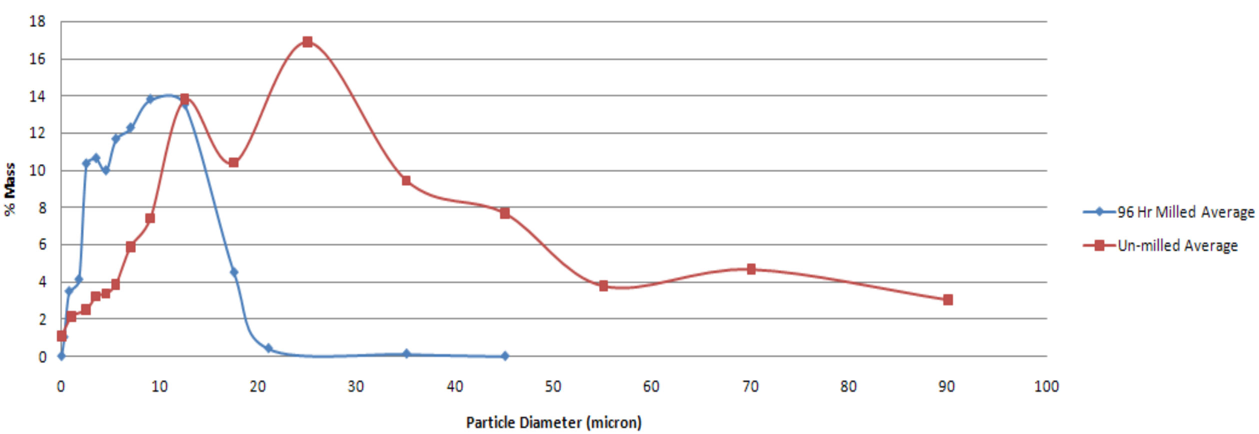
Experimental Data

# Ash Characterization

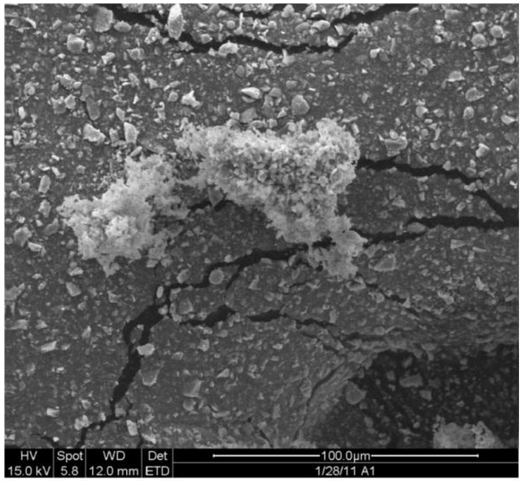
- Sub-bituminous ash from Jim Bridger Power Station (JBPS)
- Ash is milled for 96 hours to decrease particle diameter

Statistical Values for JBPS Fly Ash (microns)

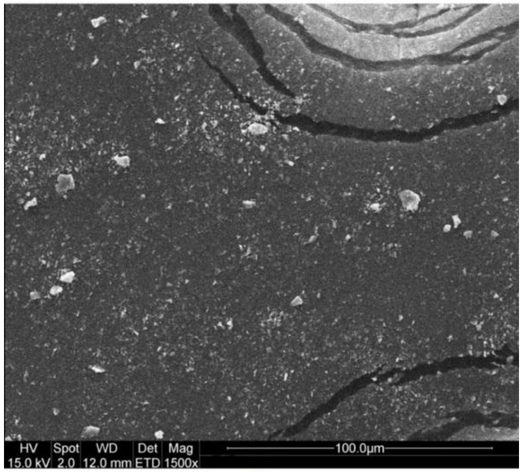
| | 96 hours | Un-milled |
|---|---|---|
| **Mean Diameter** | 6.8 | 24.4 |
| **Modal Diameter** | 8.2 | 27.0 |
| **Median Diameter** | 5.9 | 17.6 |




Averaged Particle Size Distributions for JBPS Coal Fly Ash




(a)




(b)

**Micrographs :**
a) Un-milled
b) 96 Hr. Milled JBPS

# TuRFR Test Results

| JBPS Ash Condition | Un-milled | 96 Hr. Mill | Un-milled | 96 Hr. Mill |
|---|---|---|---|---|
| Inlet Mass Flow (kg/s) | 0.38 | 0.39 | 0.39 | 0.39 |
| Mach Number | 0.084 | 0.082 | 0.076 | 0.082 |
| Inlet Temperature (°C) | 1084 | 1082 | 1083 | 1080 |
| Exit Reynolds Number | 229500 | 236500 | 245000 | 239700 |
| Film Cooling % | 7.9% | 10.1% | 0.0% | 0.0% |
| Density Ratio | 2.22 | 1.86 | N/A | N/A |
| Total Particulate Mass (g) | 300 | 251 | 292 | 329 |
| Test Time (hrs.) | 0.49 | 0.46 | 0.49 | 0.44 |
| Particle Concentration (ppmw-hr) | 221 | 178 | 205 | 234 |
| Stokes Number | 4.52 | 0.34 | 4.01 | 0.34 |

# TuRFR Test Results

Uncooled | Cooled

St ≅ 4

(a)

(b)

St ≅ 0.3

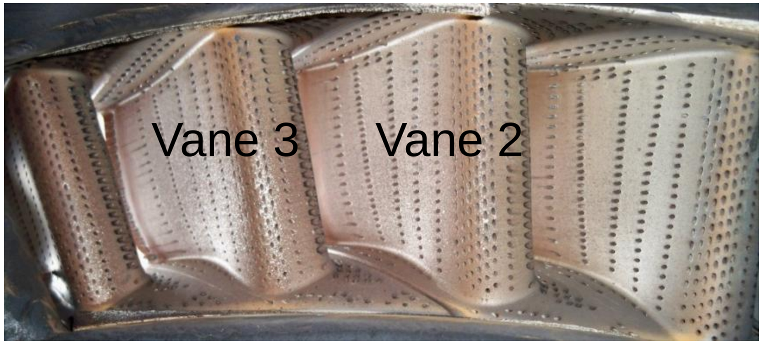
(c)

(d)

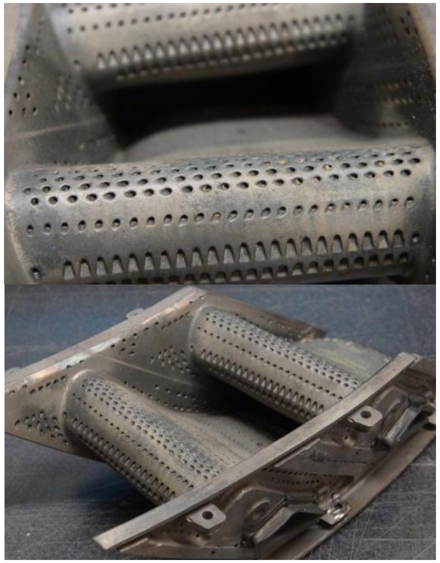
# Capture Efficiency

| Vane 3 | Large Stokes No Film Cooling | Large Stokes with Film Cooling | Small Stokes No Film Cooling | Small Stokes with Film Cooling |
|---|---|---|---|---|
| 1st Set of Tests | 27.0% | 12.2% | 9.5% | - |
| 2nd Set of Tests | 31.2% | 11.3% | 5.8% | 3.7% |

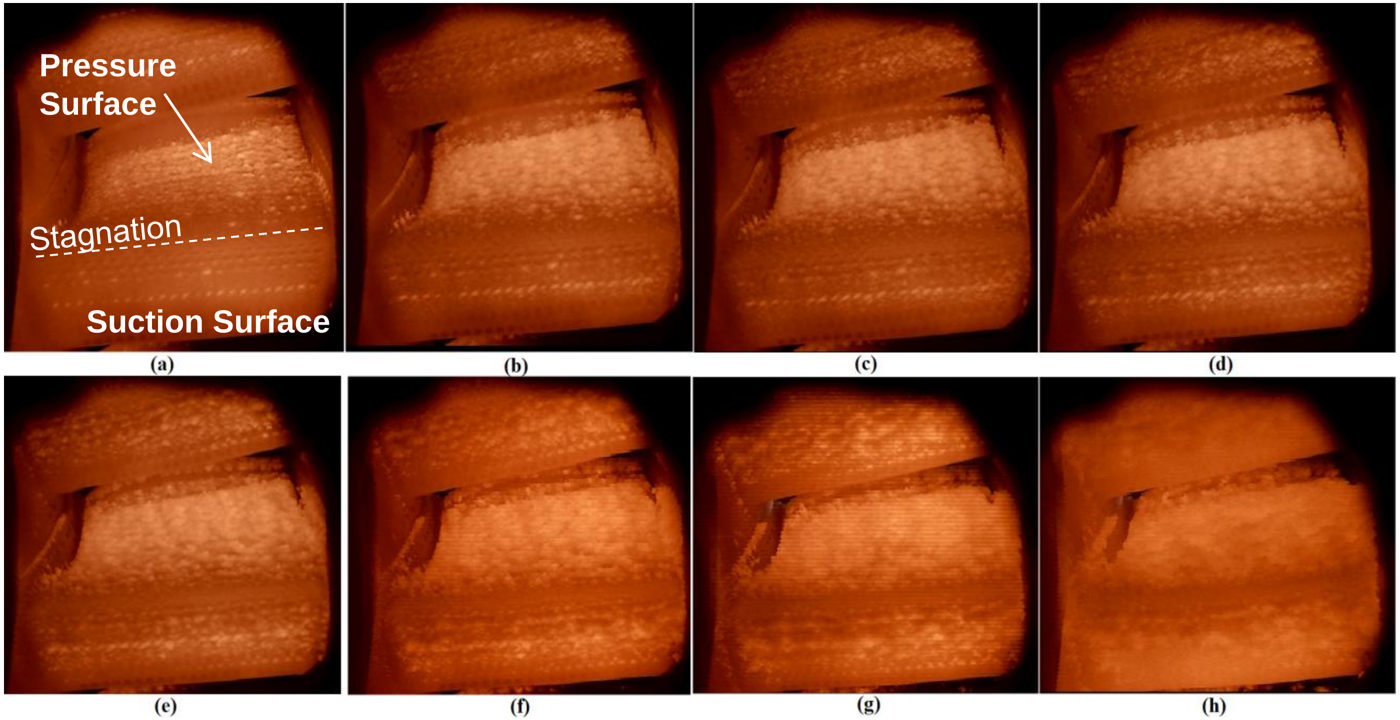
| Vane 2 | Large Stokes No Film Cooling | Large Stokes with Film Cooling | Small Stokes No Film Cooling | Small Stokes with Film Cooling |
|---|---|---|---|---|
| 1st Set of Tests | 19.9% | 7.8% | 6.6% | - |
| 2nd Set of Tests | 22.1% | 10.5% | 5.1% | 2.9% |



# No Cooling, Large Stokes



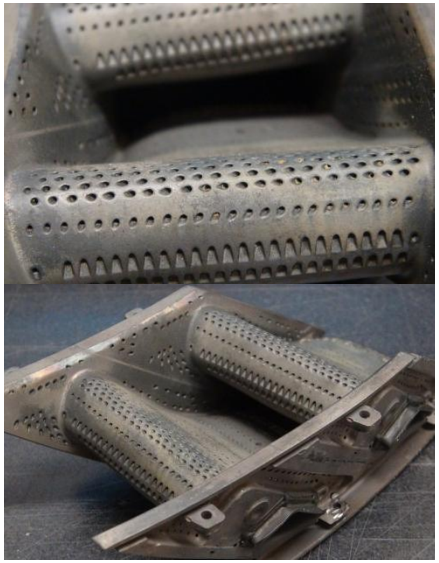
CFM 56 doublet



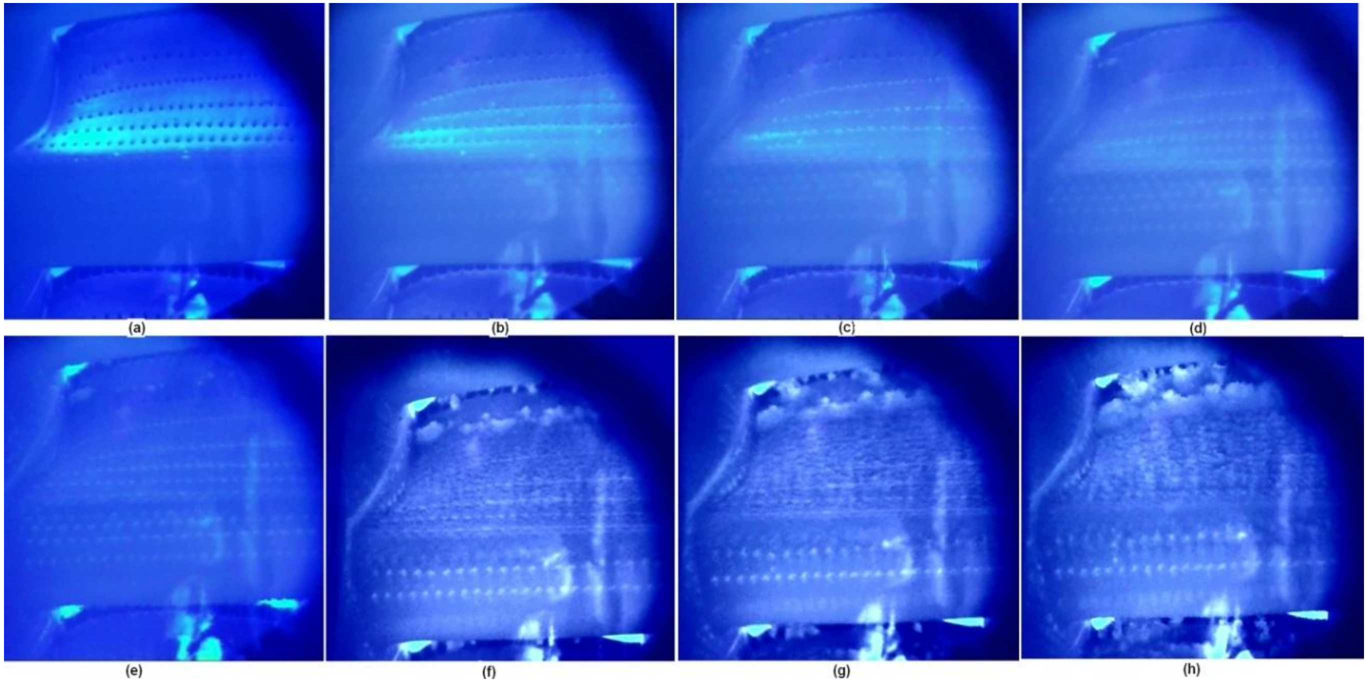

**Development of JBPS Deposit, Large Stokes Number, without Film Cooling, 292 g injected: (a) + 1 min (b) +2 min (c) +3 min (d) +5 min (e) +7 min (f) +13 min (g) +20 min (h) +30 min**

- Deposits begin to develop past mid-chord on the pressure surface and move forward toward the leading edge.
- Same progression on the suction side
  - Deposits on suction side only occur close to the leading edge

# No Cooling, Small Stokes



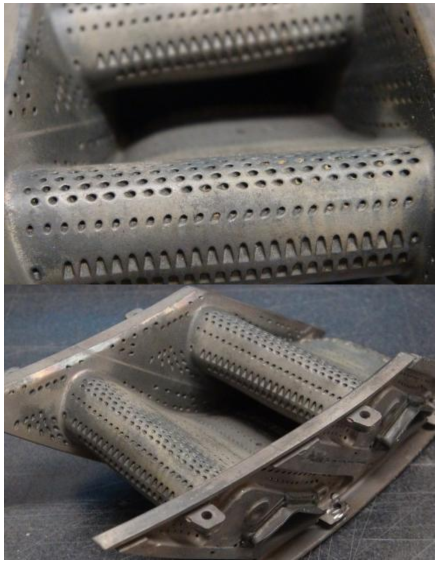
**CFM 56 doublet**



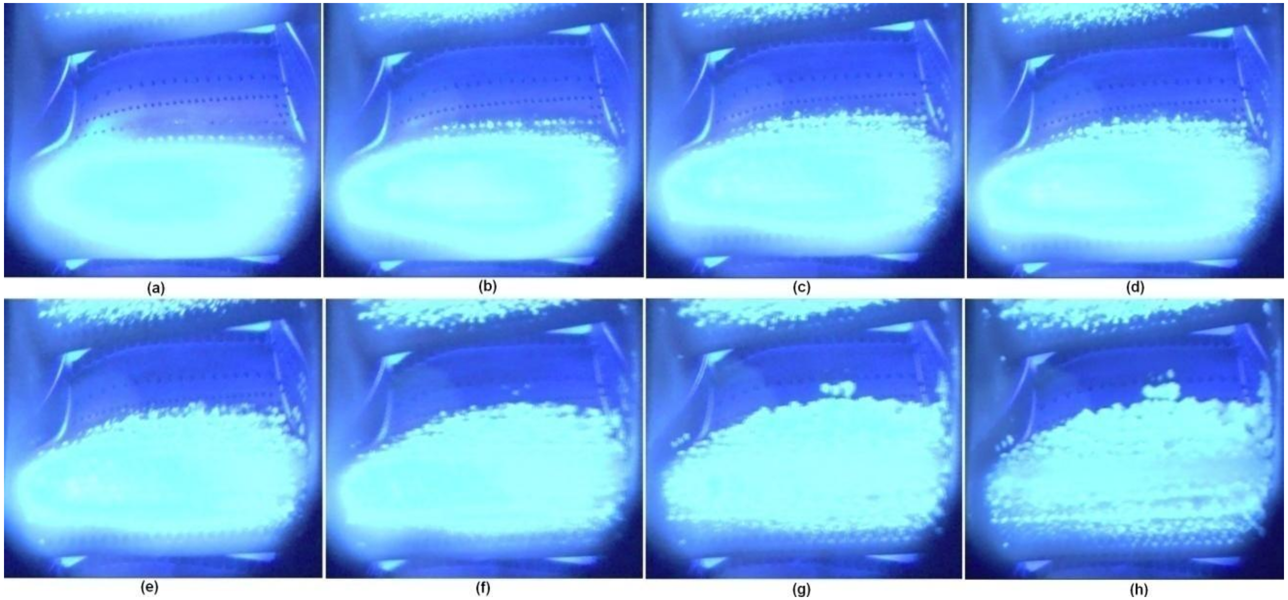

**Development of JBPS Deposit, Small Stokes Number, without Film Cooling, 329 g injected: (a) + 1 min (b) +2 min (c) +4 min (d) +5 min (e) +7 min (f) +13 min (g) +20 min (h) +30 min**

- Deposits develop in and around film cooling holes first.
- Higher accumulation is seen on the pressure surface towards the trailing edge.
- Much less overall deposit accumulation when compared to the large Stokes test.

# 9% Cooling, Large Stokes



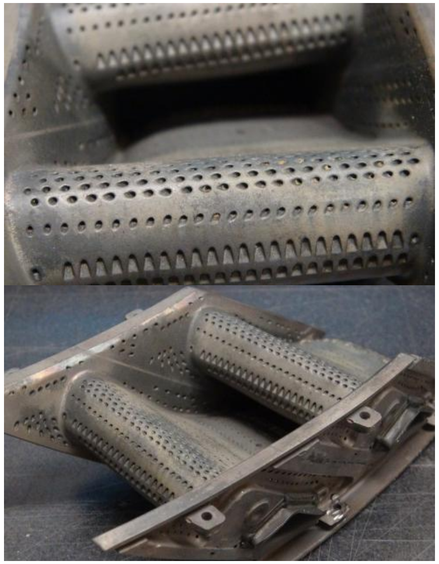
CFM 56 doublet



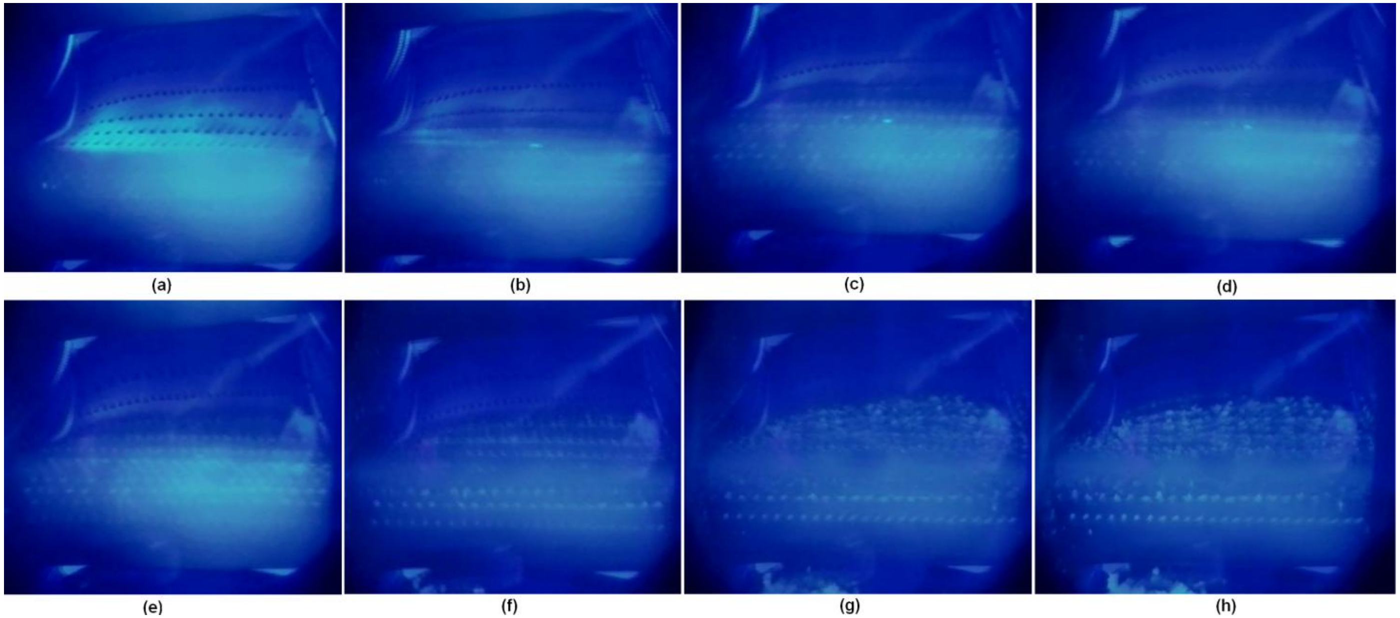

**Development of JBPS Deposit, Large Stokes Number, with Film Cooling, 300g injected: (a) + 1 min (b) +2 min (c) +4 min (d) +5 min (e) +7 min (f) +13 min (g) +20 min (h) +30 min**

- Deposition with film cooling begins on the leading edge, inside film cooling holes and remains more concentrated towards the leading edge.
    - No deposition past 60% chord
- Thick deposits present due to the large diameter of the particles

# 9% Cooling, Small Stokes



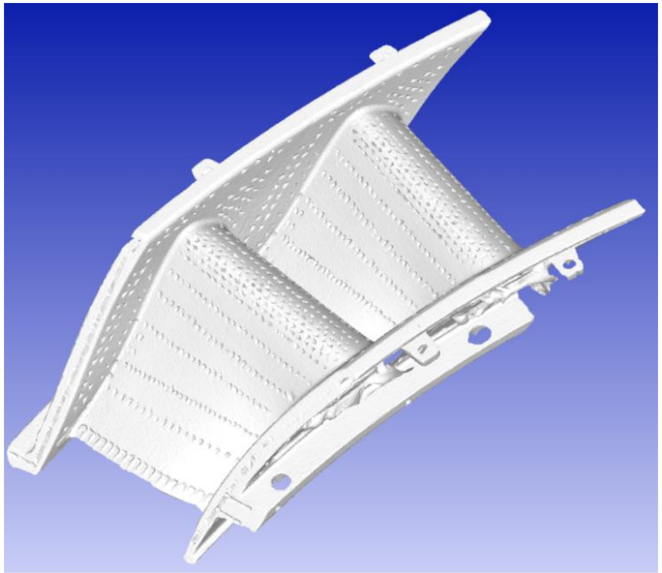
CFM 56 doublet



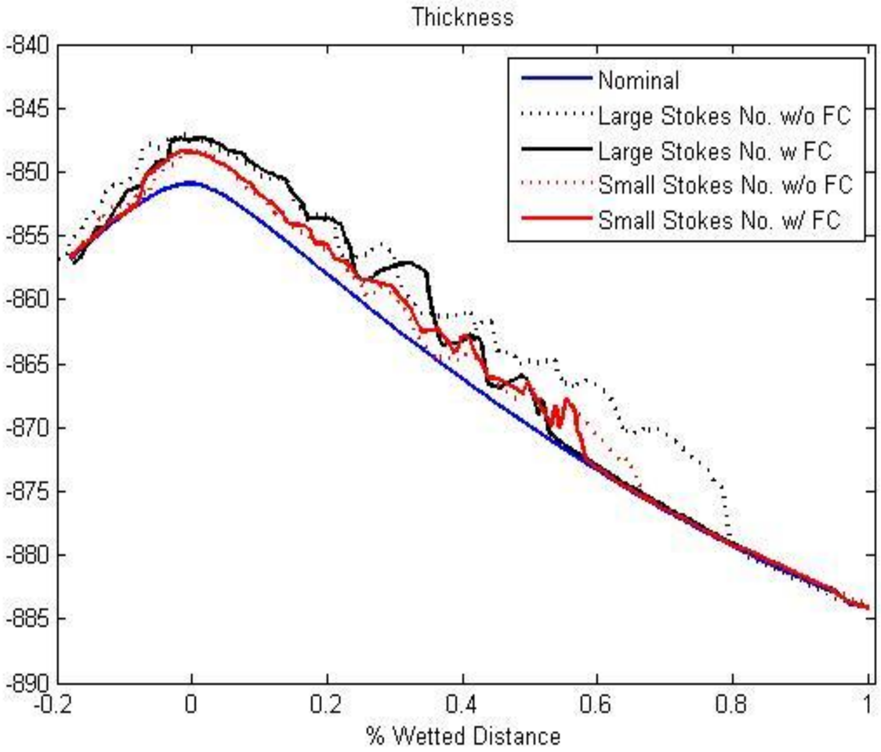

**Development of JBPS Deposit, Small Stokes Number, with Film Cooling, 251g injected: (a) + 1 min (b) +2 min (c) +3 min (d) +5 min (e) +7 min (f) +13 min (g) +20 min (h) +30 min**

- Deposition begins inside film cooling holes towards the leading edge
  - No deposition past 60% chord
- Thinner deposits than seen for the large Stokes number test.

# Surface Metrology



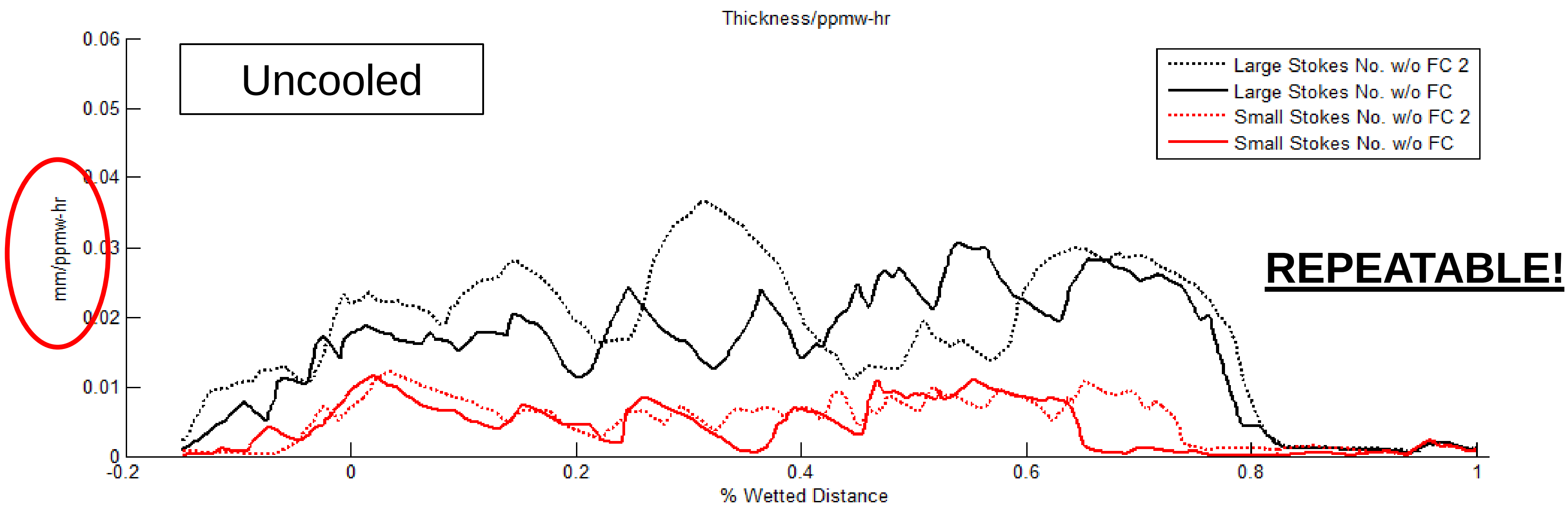
Laser Scan of Nozzle Guide Vane Doublet

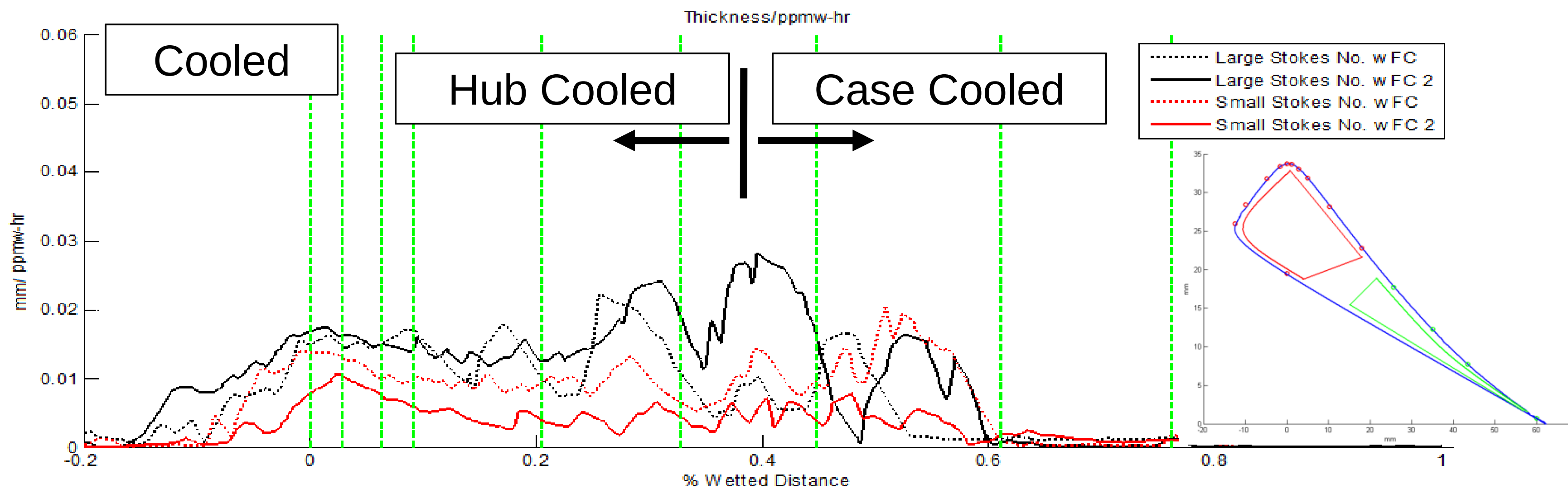



Mid-span Trace of Deposit Thickness with Nominal Vane

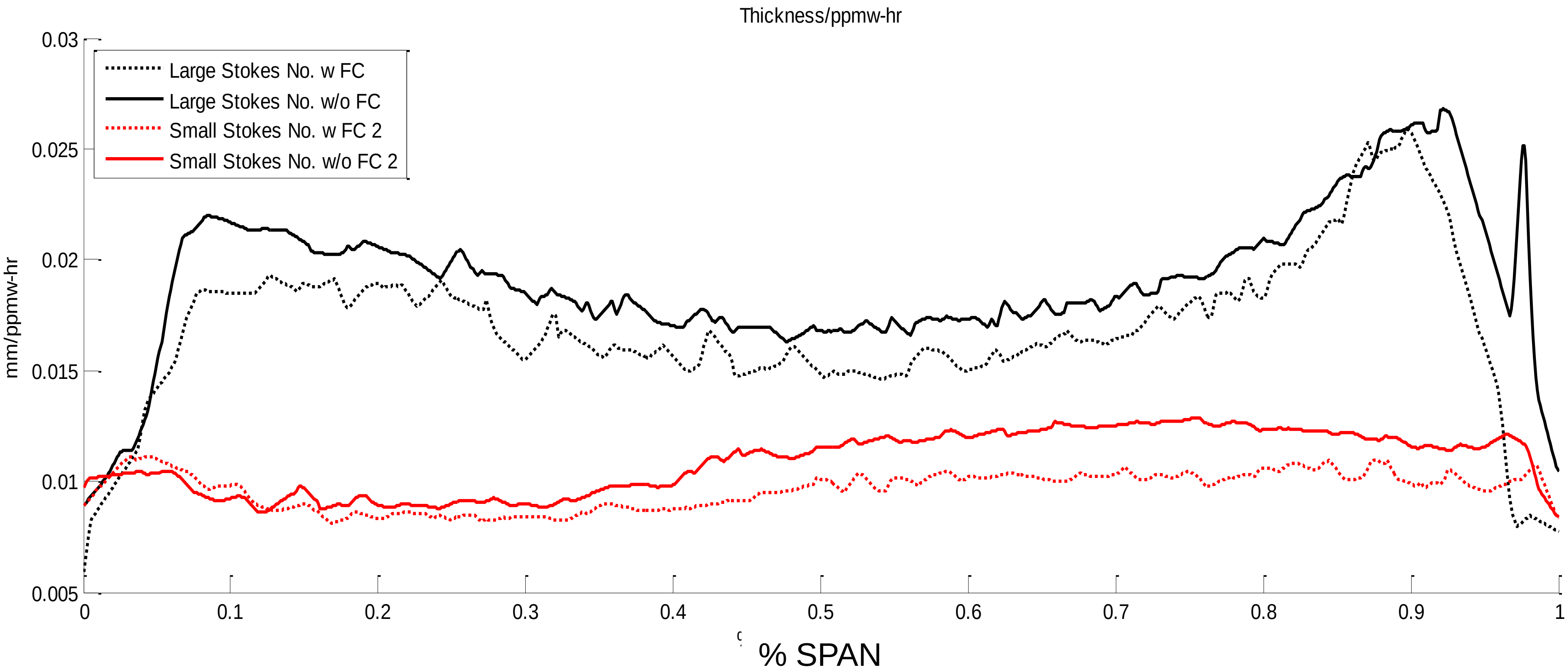
- CMM Optical laser scan before and after deposition to acquire deposit thickness distribution

# Mid-span Thickness Distribution



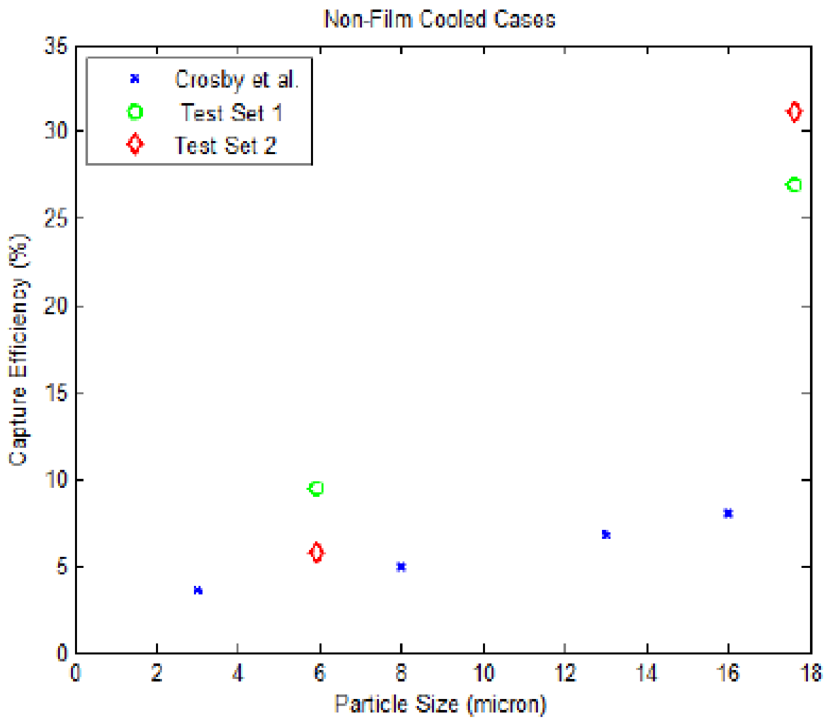



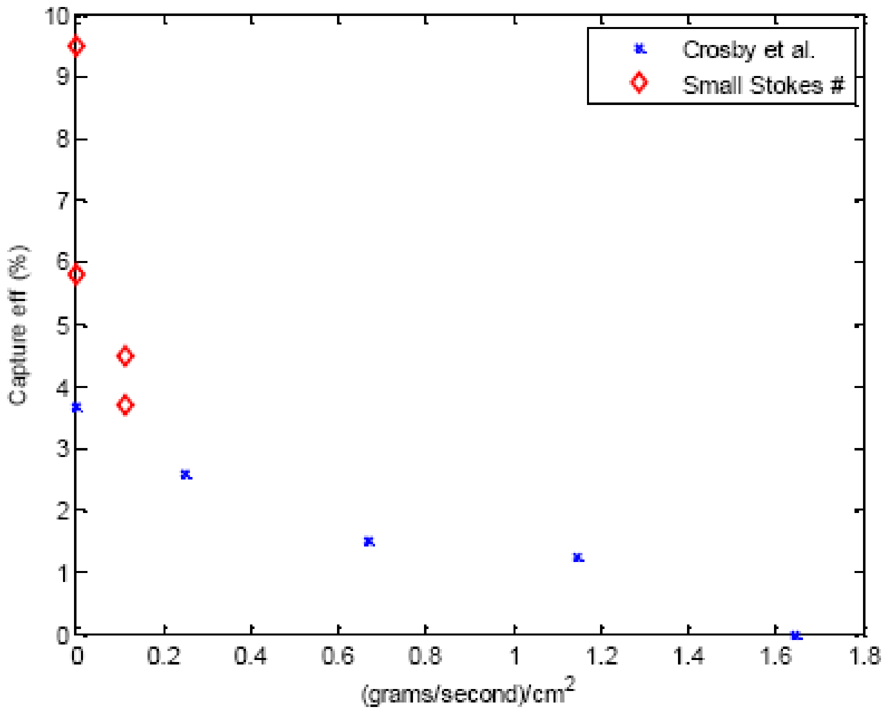
# LE Thickness Distribution




- 10-20% reduction due to cooling
- 60-70% reduction due to Stokes
- Large Stokes more susceptible to secondary flows near endwall

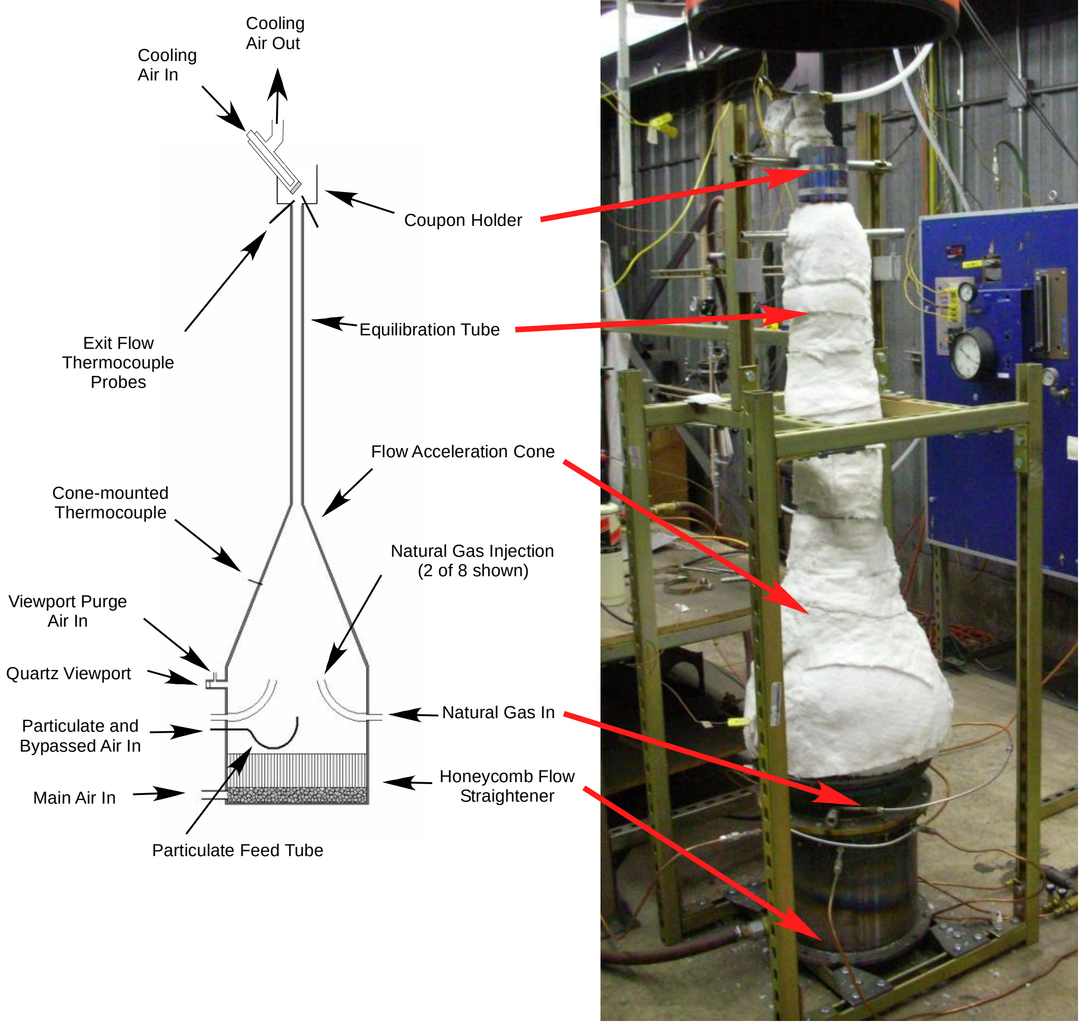
# Comparison with TADF



# BYU Results/Progress

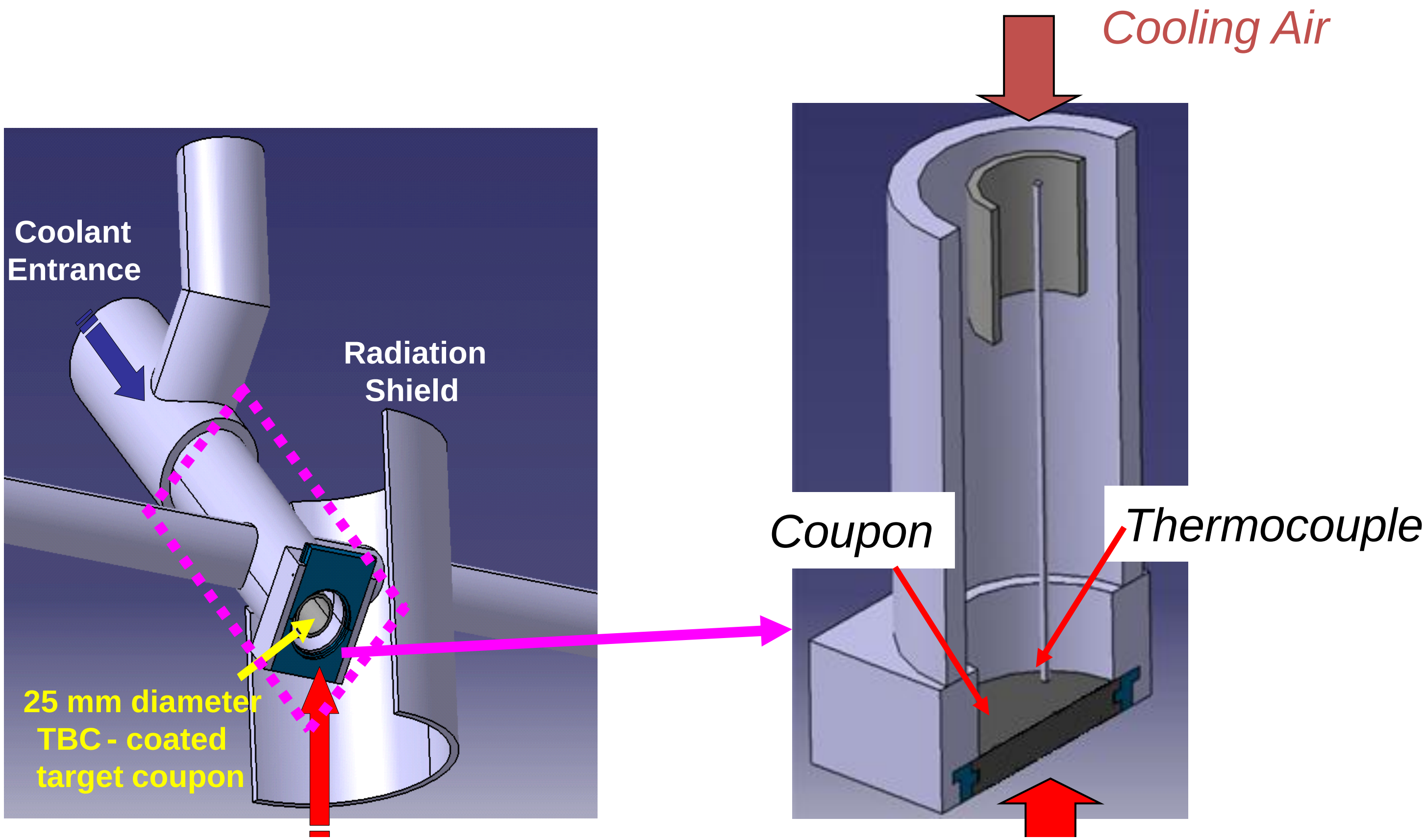
# BYU Deposition Facility (TADF)




- Design Parameters to match: temp, velocity, angle, materials, particle size, chemistry, and concentration
- Inconel construction allows max jet temperature of 1200°C
- Exit velocities up to 300m/s – deposition by inertial impaction
- Target coupons supplied from industry
- Capability for impingement and film cooling
- Match net particle throughput

**8000 hrs $\times$ 0.1 ppmw ≈**
**4 hrs $\times$ 200 ppmw**

# BYU Coupon Holder




*Deposit-laden combustor exhaust at 1183 ℃*

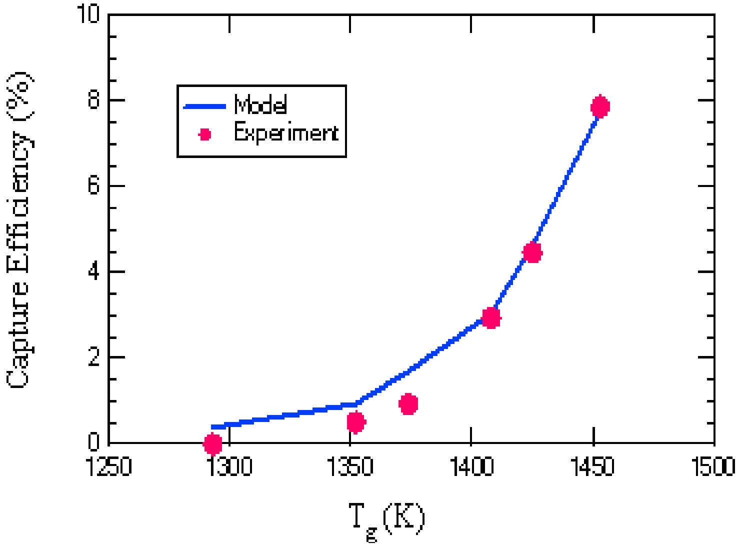
*Deposit-laden combustor exhaust at 1183 ℃*

Coupons generally held at 45° angle to flow

# BYU – Previous Testing

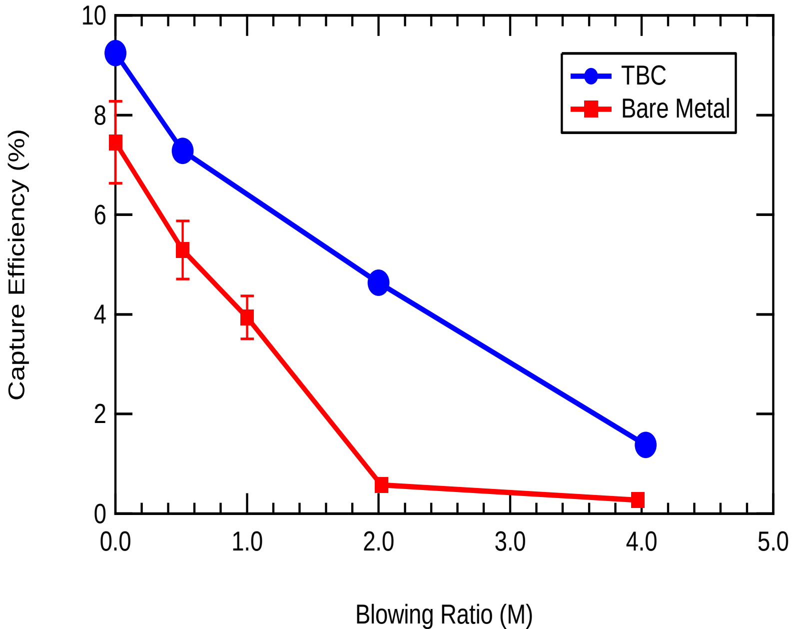
## Deposition vs. Temperature

- Deposition increases with gas exit temperature
- Insulated tests conducted up to 1150°C (i.e., no cooling)
- No deposition below ~950°C




## Deposition vs. Cooling

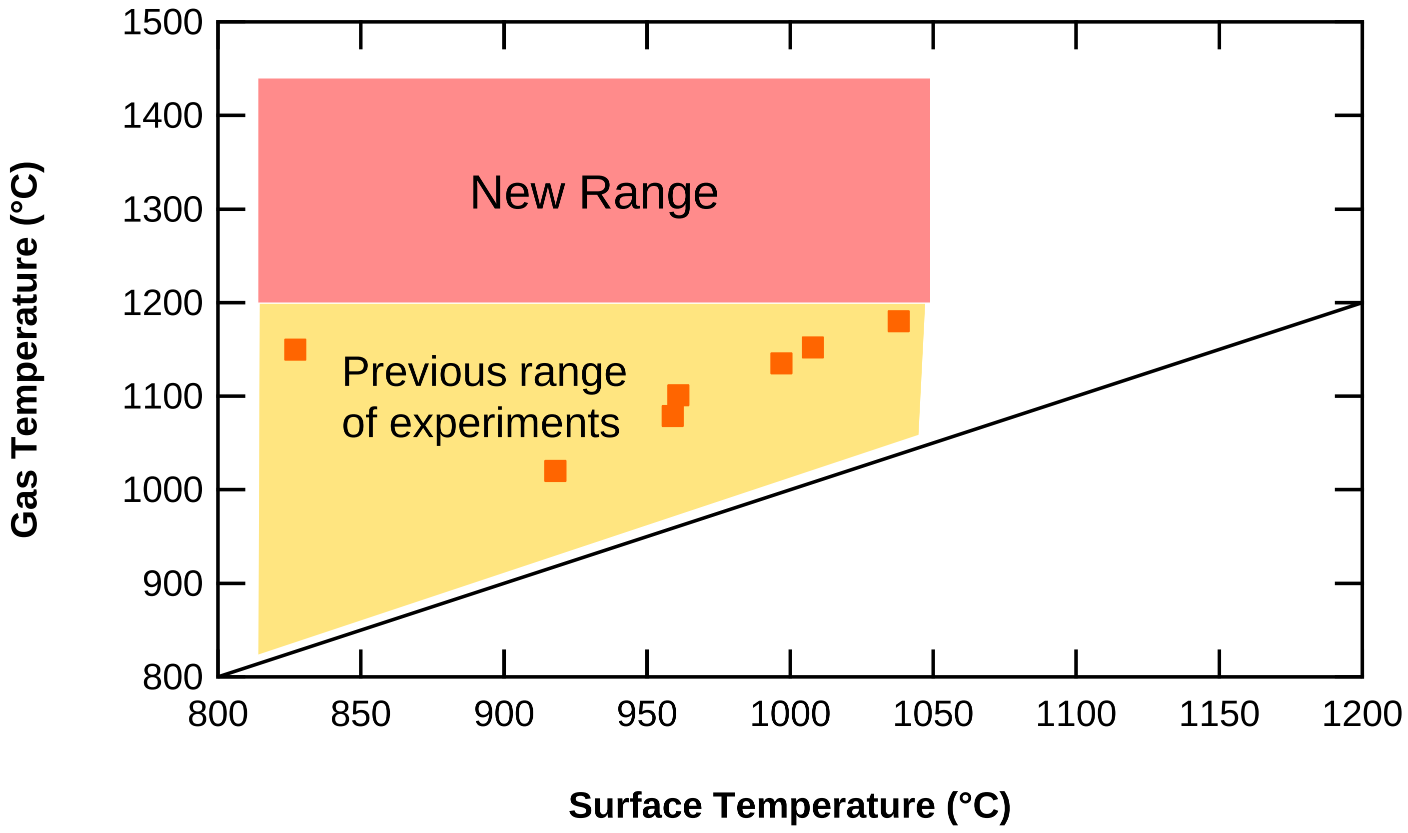
- Deposition decreases with increasing coupon cooling
    - backside cooling
    - film cooling on surface



# Current Research

- High temperature deposition testing at BYU
  - Modified deposition facility to operate at gas temperature ($T_g$) up to 1400 °C
- Why test at high temperatures?
  - Previous tests were performed at a $T_g$ of 1150 °C
    - Modern H-class turbines operate at $T_g$ closer to 1400 °C
    - 1150 °C is near the threshold $T_g$ of 950 °C as reported by Crosby et al. (2008)
    - Testing at higher temperatures will distinguish between the effects of gas temperature ($T_g$) and surface temperature ($T_s$)

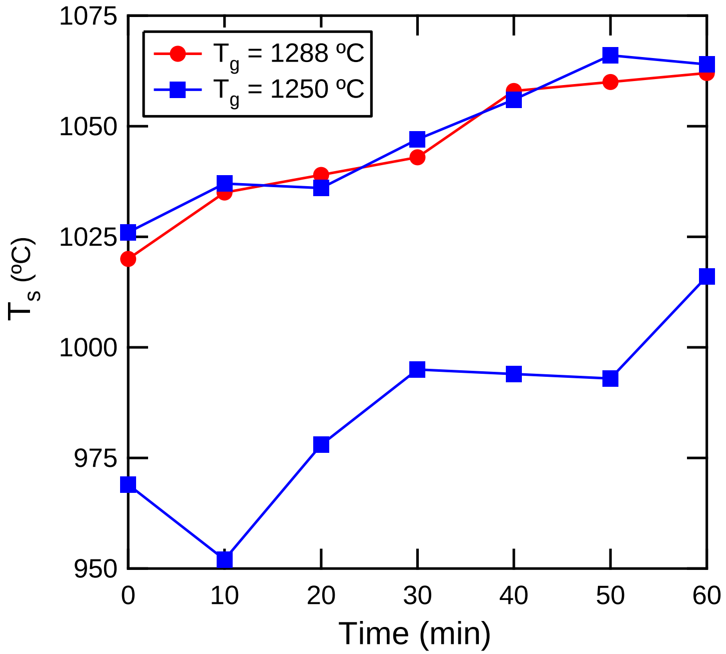
# Temperature Range



# Current High Temperature Testing

- Two main test series are underway, but not yet completed
  1. Maintain the initial surface temperature ($T_s$) and vary the gas temperature ($T_g$) from 1250°C to 1400°C
  2. Maintain $T_g$ at 1400°C and vary $T_s$
- Objective
  - Better understand influence of $T_g$ and $T_s$ individually on particle deposition
  - Accurately model particle deposition based on $T_g$ and $T_s$

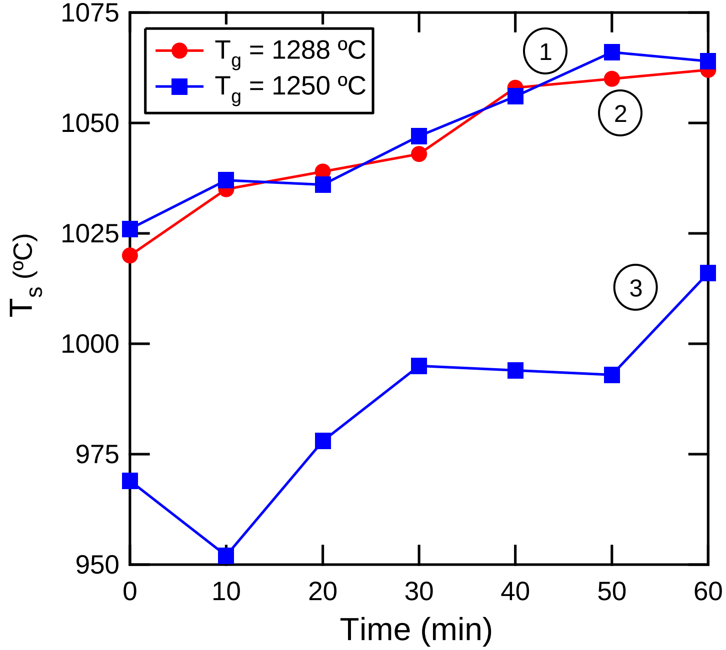
# Results: Deposition vs. $T_s$

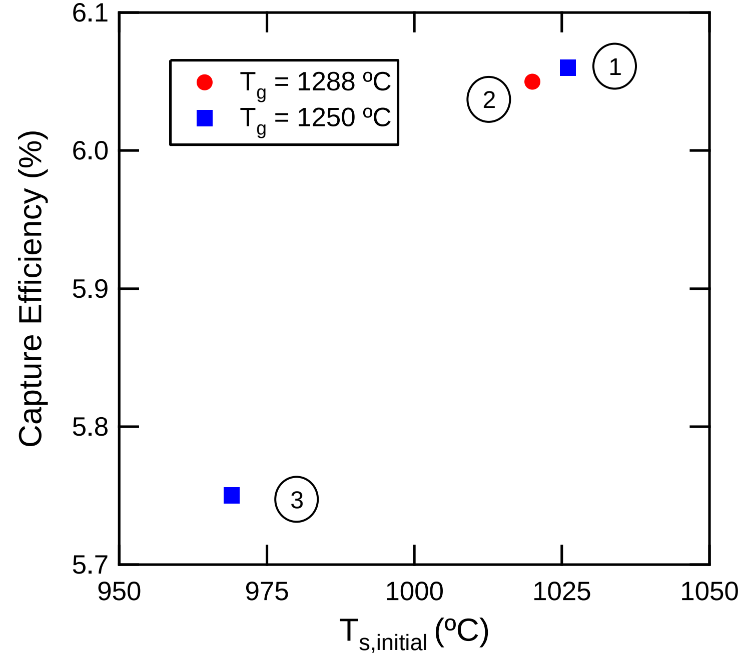



- 5 tests have been completed, but $T_s$ data are only available for 3 tests
- At increased time, deposit grows and surface temperature increases
- Two tests had different $T_g$, but started with similar $T_{s,initial}$
  - $T_s$ profiles of these two tests were similar
- Third test performed
  - High $T_g$ (1288°C) but lower $T_s$ due to coolant escaping on edges of coupon

# Results: Deposition vs. $T_s$

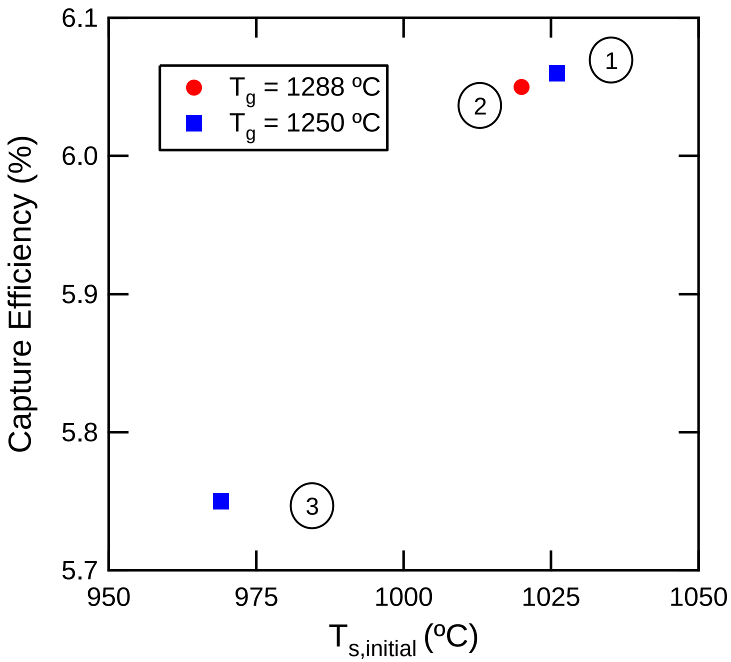
(preliminary findings)

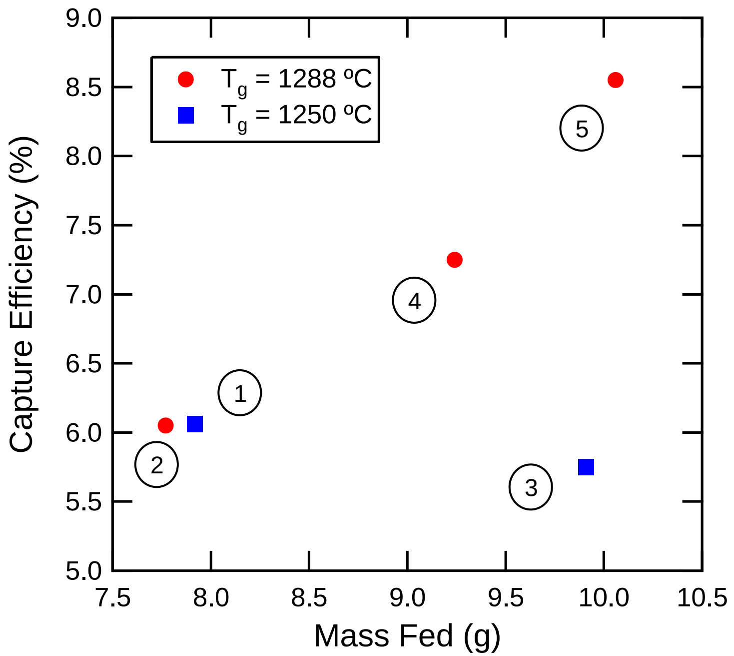



- Compare points 1 and 2
  - Different $T_g$, similar $T_s$
  - Similar capture efficiencies!
- Compare points 1 and 3
  - Same $T_g$, different $T_s$
  - Different capture efficiencies!

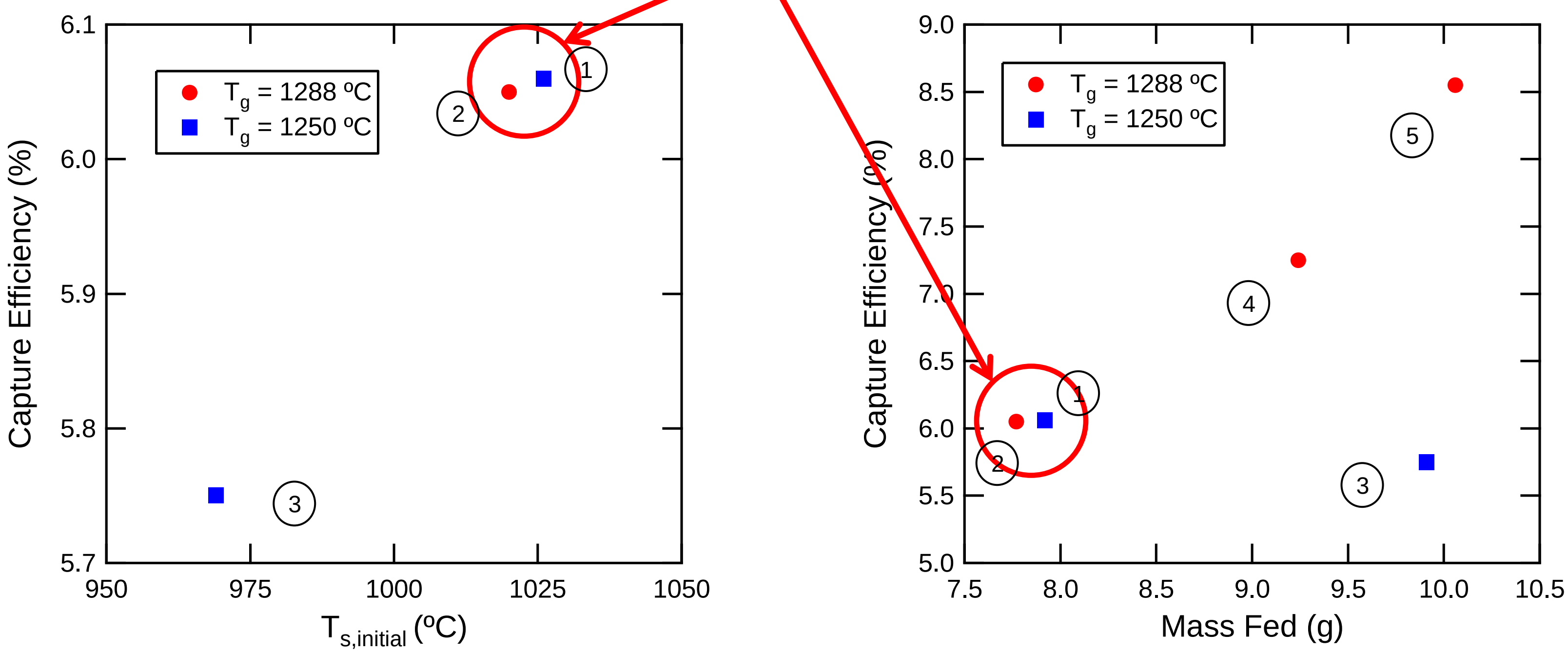
# Capture Efficiency vs $T_s$ and Particle Loading




Capture efficiency is seen to increase with both $T_{s,initial}$ and mass of ash particulate in gas stream

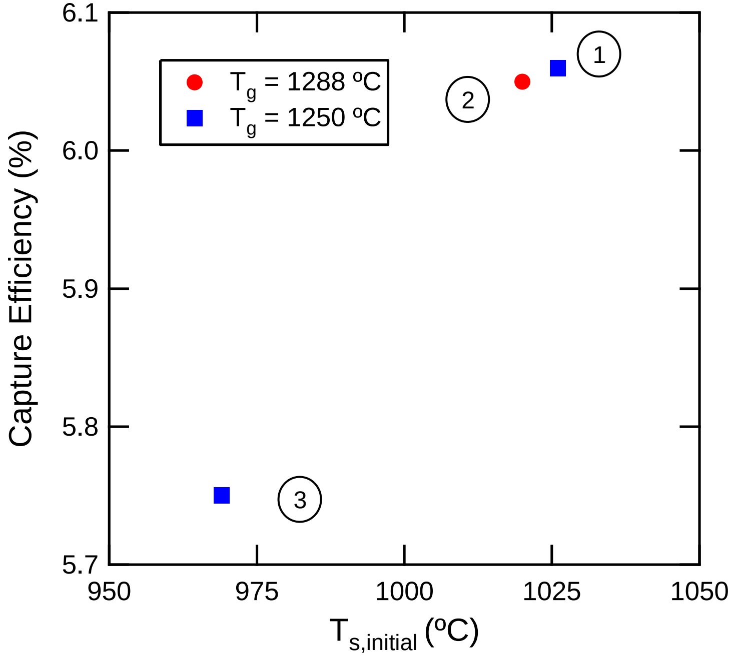
# Capture Efficiency vs $T_s$ and Particle Loading

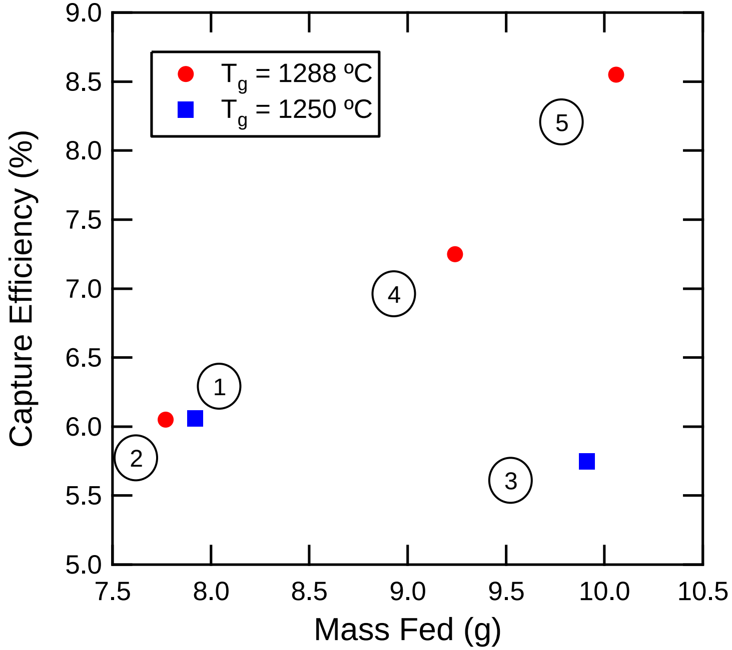



Compare tests 1 and 2

- Different $T_g$, but similar $T_{s,initial}$
- Mass throughput similar
- Result: similar capture efficiencies

# Capture Efficiency vs $T_s$ and Particle Loading




Compare points 2, 4, and 5:

- For $T_g$ = 1288 °C , capture efficiency is seen to increase with mass throughput

Compare points 1 and 3:

- For $T_g$ = 1250 °C , the test with lower $T_{s,initial}$ resulted in a lower capture efficiency despite the higher mass throughput

# Conclusions

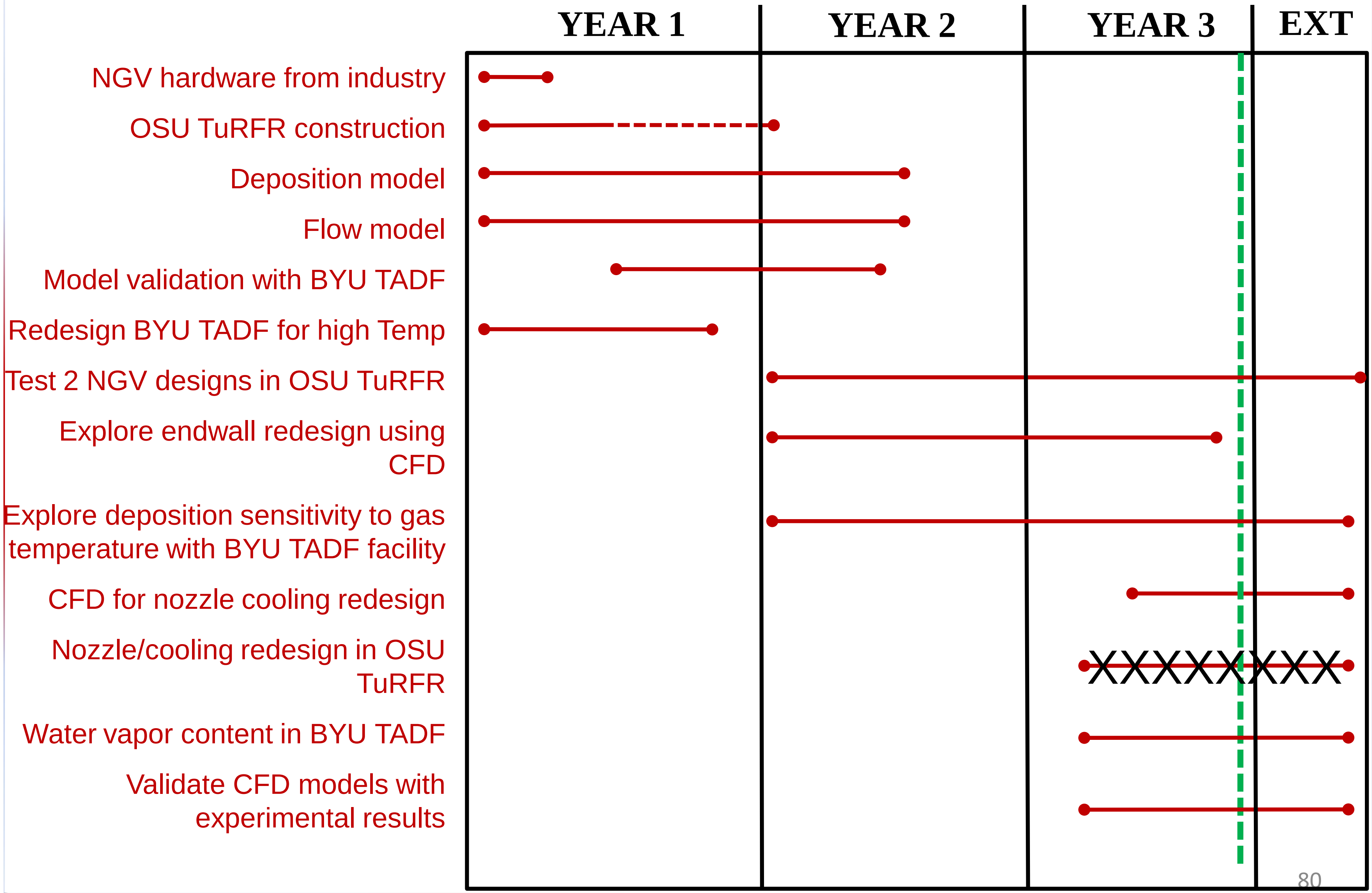
Tests have been completed at the lower end of the desired range of $T_g$

- An increase in surface temperature led to an increase in capture efficiency
- For the tests in which $T_g$ and $T_s$ were known, variation in $T_g$ did not have an effect on capture efficiency
- Tests with similar $T_{s,initial}$ but different $T_g$ developed in a similar manner
- Tests with similar $T_g$ and increasing particle loading had increased capture efficiency
- $T_s$ seems to have a greater effect than particle loading on capture efficiency

# BYU - Future Work

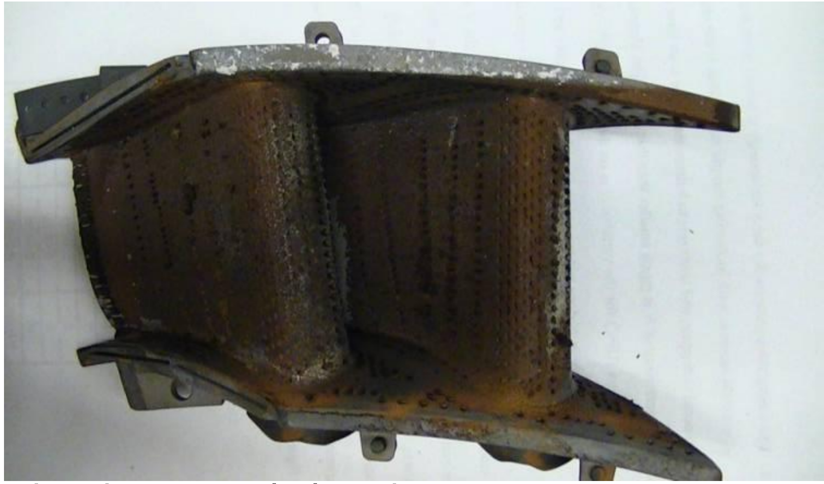
- Complete current temperature test series (i.e., with backside cooling)
- Perform film cooling test series at high gas temperatures (up to 1400°C)
- Perform tests with higher water concentration (up to 15 mol%)

# Program Schedule



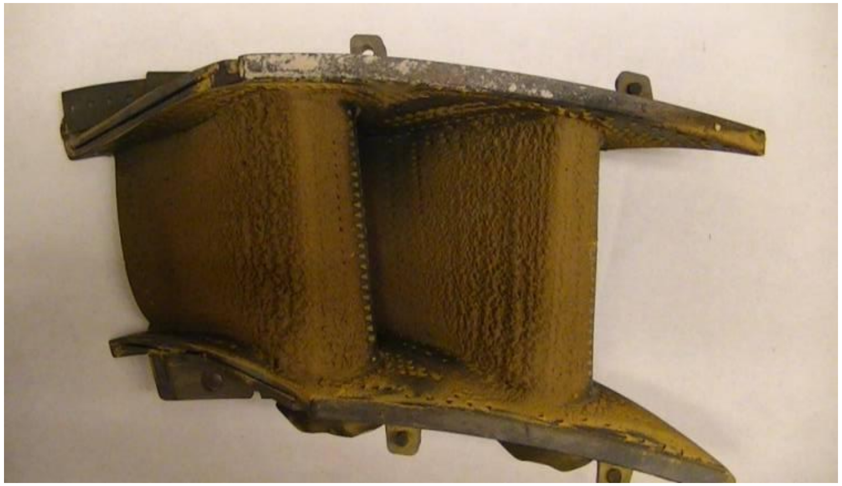

QUESTIONS?

# Results with Different Ash



Bituminous Coal Fly Ash
- Limited deposition up to 2050F – High Iron

Lignite Coal Fly Ash
-Thickest deposits at lowest temperature (1900F)

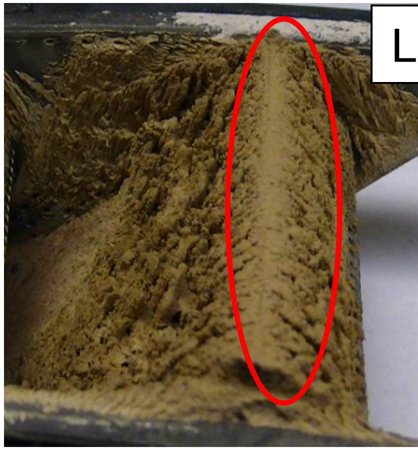


PRB Subbituminous Coal Fly Ash
- Significant deposition above 1920F – High Calcium

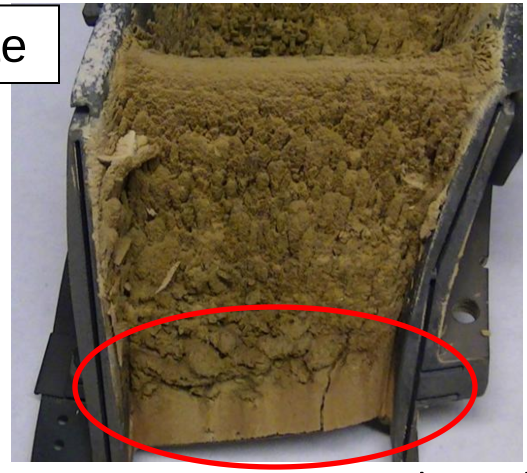
“BYU” Subbituminous Coal Fly Ash
- Comparable deposits to PRB – High Silicon

# Results with Different Ash

Lignite

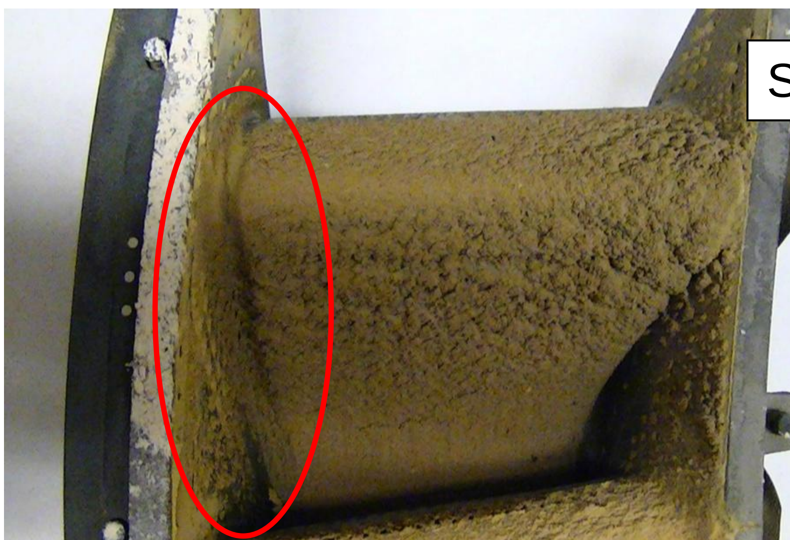


Leading edge stagnation line well defined



Large structures near trailing edge. Smooth deposits last 20%.

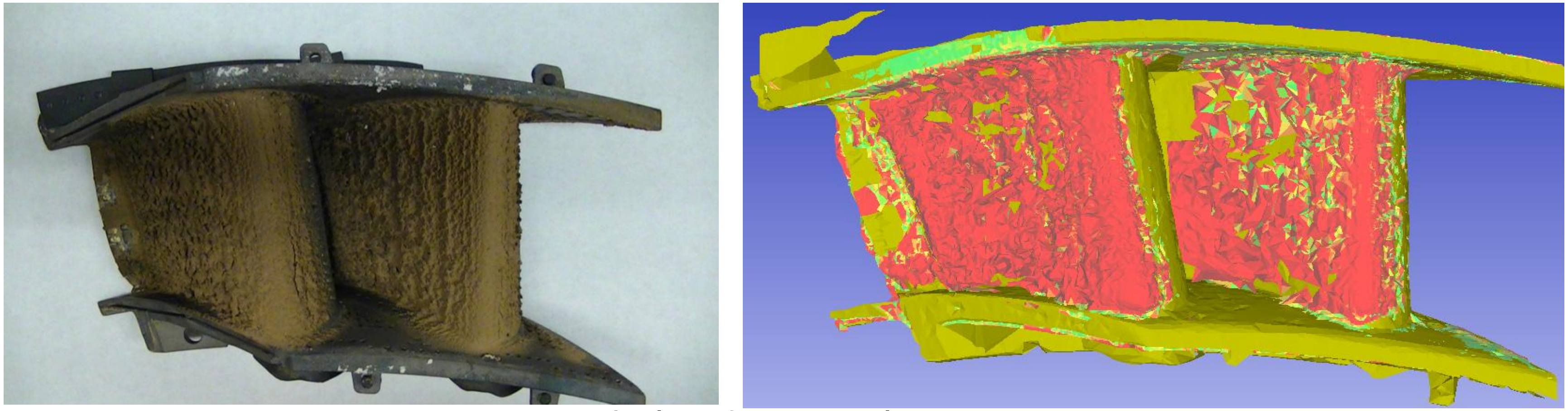
Subbituminous



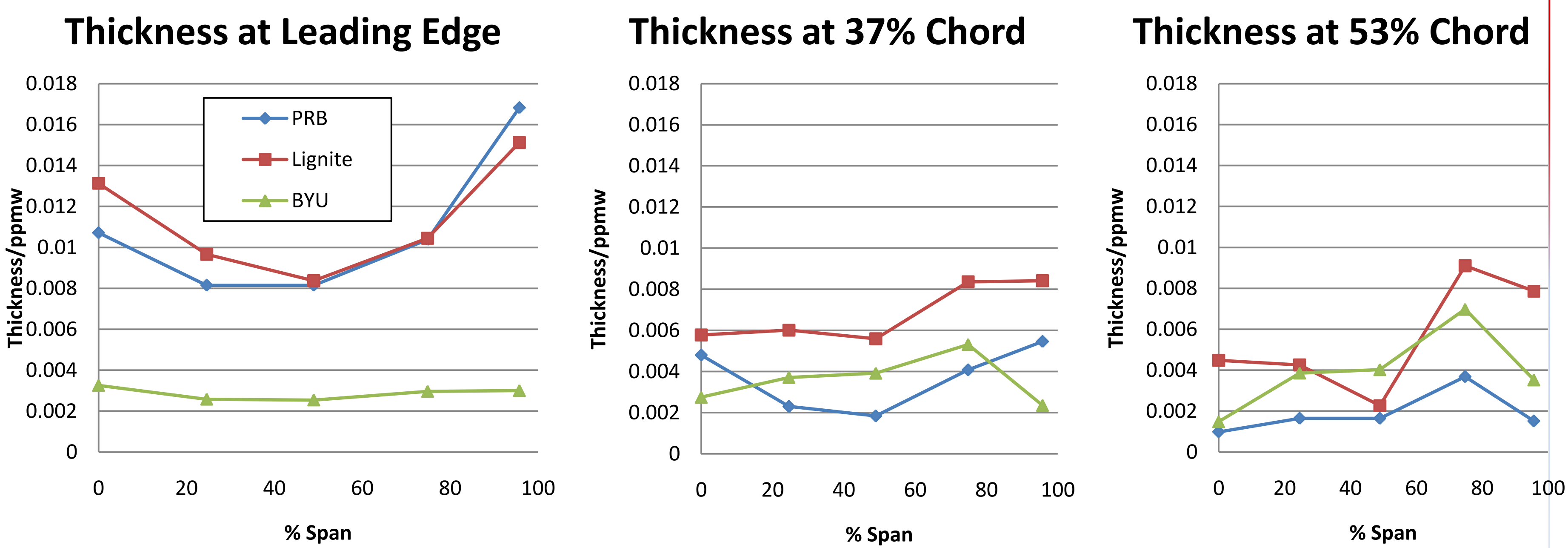
Evidence of secondary flows on casing (and hub) endwall.

Jagged structures develop in upstream direction on pressure surface. Terminate toward suction surface.

# Results with Different Ash



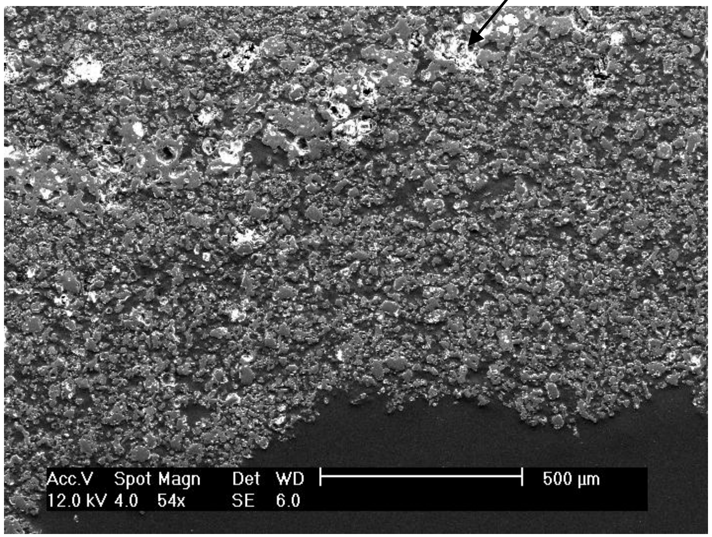
Optical Surface Metrology



# Results with Different Ash

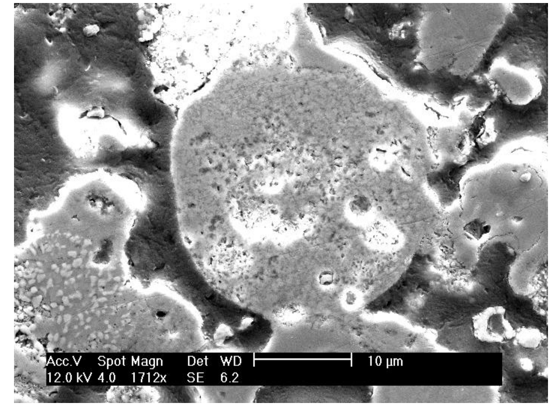
PRB Subbituminous

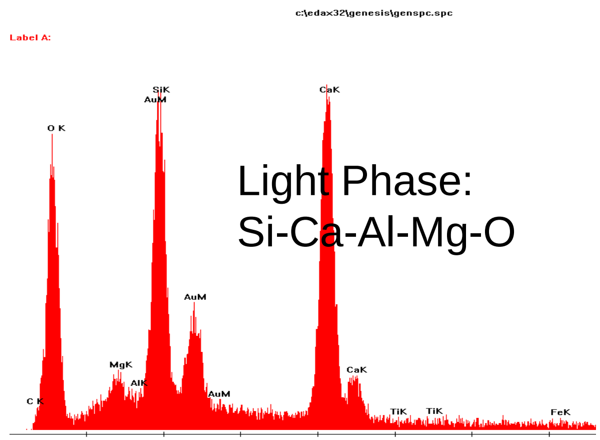
Vein of more dense material



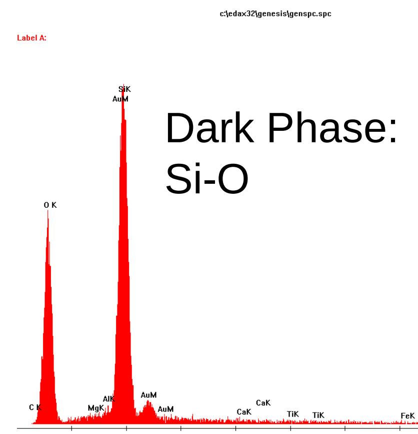

(Bottom of deposit)

Light and dark phases observed throughout the entire sample



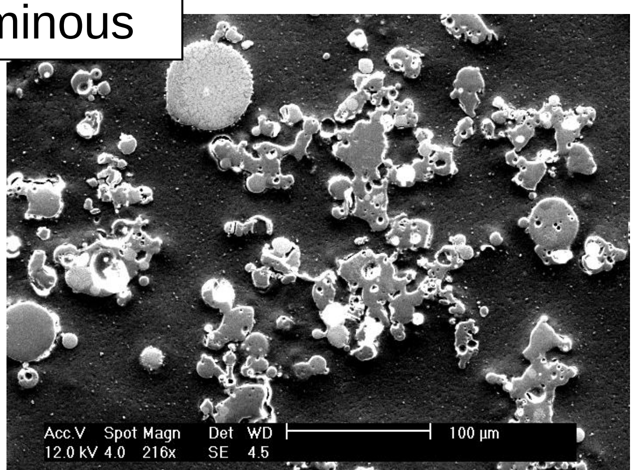




Light Phase:
Si-Ca-Al-Mg-O




Dark Phase:
Si-O

Bituminous




Very High Porosity

*Courtesy of Dr. Nitin Padture's Materials Lab